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HELICOPTER ROLL CONTROL EFFECTIVENESS CRITERIA PROGRAM SUMMARY

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Contract NAS2-11665
April 1988

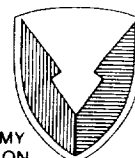
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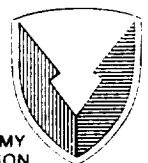
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ABSTRACT

A study of helicopter roll control effectiveness is summarized for the purpose of defining military helicopter handling qualities requirements. The study is based on an analysis of pilot-in-the-loop task performance of several basic maneuvers. This is extended by a series of piloted simulations using the NASA Ames Vertical Motion Simulator and selected flight data. The main results cover roll control power and short-term response characteristics. In general the handling qualities requirements which are recommended are set in conjunction with desired levels of flight task and maneuver response which can be directly observed in actual flight. An important aspect of this, however, is that vehicle handling qualities need to be set with regard to some quantitative aspect of mission performance. Specific examples of how this can be accomplished include a lateral unmask/remask maneuver in the presence of a threat and an air combat tracking maneuver which recognizes the kill probability enhancement connected with decreasing the range to the target. Conclusions and recommendations address not only the handling qualities recommendations, but also the general use of flight simulators and the dependence of mission performance upon handling qualities.

FOREWORD

This report was prepared by Manudyne Systems, Inc., for the Aeroflightdynamics Directorate, U. S. Army Aviation Research and Technology Activity located at Ames Research Center. The Contract Technical Monitors were Ms. Michelle M. Eshow and Mr. Christopher L. Blanken.

Manudyne was assisted by Professor Howard C. Curtiss, Jr., of Princeton University, Mr. William S. Hindson of Stanford University, and Dr. Ronald A. Hess of University of California at Davis.

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Personnel providing simulation support included: Mr. David L. Astill, Mr. Matt Blake, Mr. Greg Bookout, Mr. Richard S. Bray, Mr. James A. Jeske, Mr. Michael Lewis, Mr. Joseph Ogwell, Mr. Russ Sansom, and Ms. Liza Tweton.

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ROLL CONTROL EFFECTIVENESS FOR MILITARY ROTORCRAFT

--PROGRAM SUMMARY

I. INTRODUCTION

This report contains a summary of research performed to define roll control effectiveness requirements for military rotorcraft. This research was sponsored by the U. S. Army Aeroflightdynamics Directorate at Ames Research Center and was based chiefly on simulator experiments performed by Manudyne on the NASA Ames Vertical Motion Simulator (VMS).

This work is intended to support concurrent efforts to update the helicopter handling qualities specification, MIL-H-8501A (Reference 1). A version of the specification update developed for the Army's Light Helicopter Family (LHX) can be found in Reference 2 in which are reflected some of the results of this program.

Results from the first phase of the study reported here are contained in Reference 3 (the first-phase final report) and several technical papers, including References 4 through 7. This report includes material from these earlier reports and papers in addition to more recent analyses and results.

A. Background

Roll control effectiveness is a primary ingredient of aircraft design. It determines how well any task involving rolling and lateral motion is performed and sets important constraints on rolling moment, damping, and manipulator sensitivity. Roll control effectiveness impacts not only basic handling qualities and task performance, but also has important structural design implications.

The topic has been studied a number of times prior to this program. Unfortunately previous results such as depicted in the traditional plot of roll damping versus roll sensitivity shown in Figure 1 provide no clear consensus for the designer.

The diversity of results obtained from various handling qualities experiments or the scatter within a single experiment is often not considered or explained. One is left to assume the vagaries of experimental procedure, simulator fidelity, task dependence, and pilot-to-pilot variation. But there may be a number of particularly compelling reasons. Some of the problems and aspects which may not have been adequately considered in prior research include the following.

SOURCES

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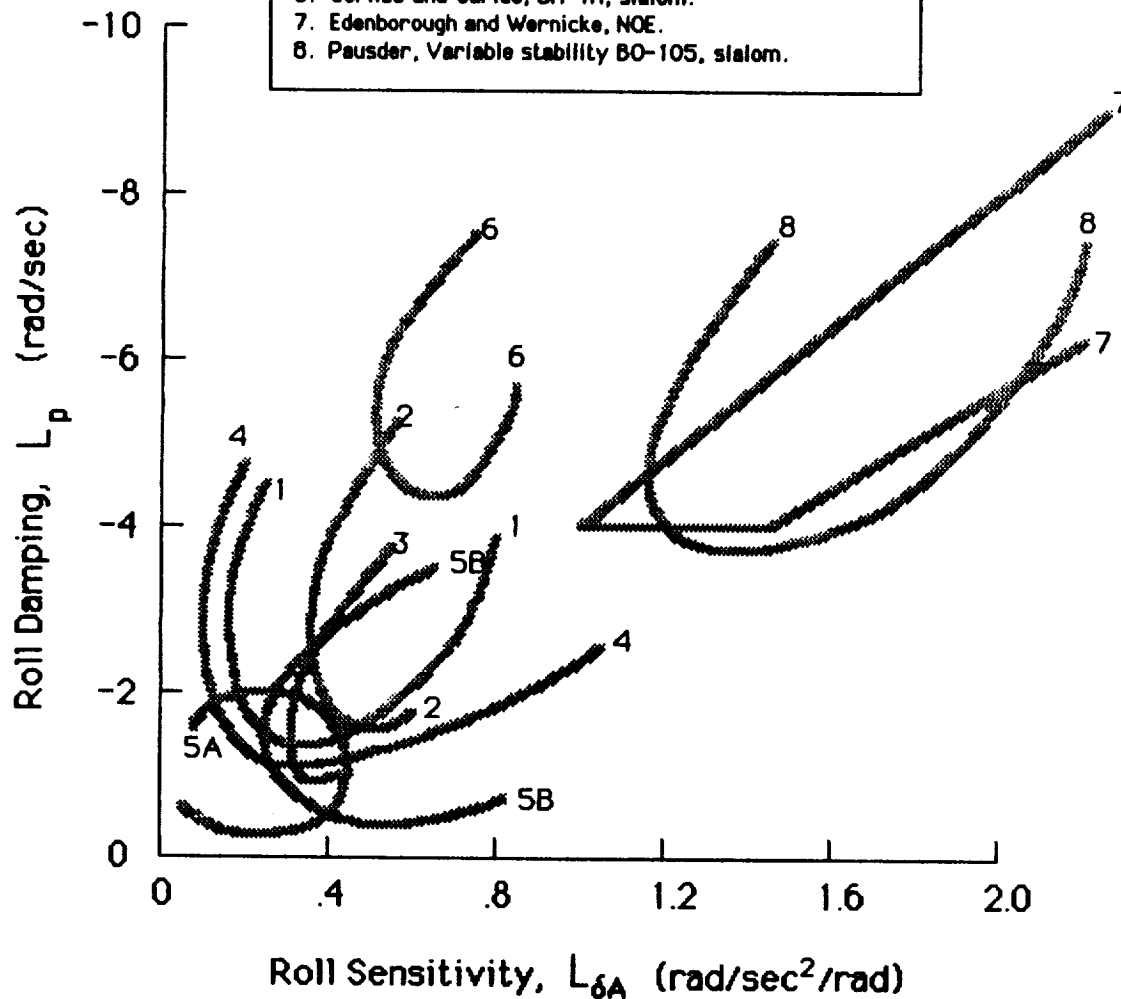


Figure 1. Level 1 Iso-Opinion Boundaries for Roll Damping and Control Sensitivity from Various Sources.

1. Role of Handling Qualities in Supporting Mission Performance

It has been traditional to consider "performance" as separate from "handling qualities" or "stability and control." In fact, one can show that there can be rather strong and direct linkage between the ability to extract a given level of aircraft or mission performance and the "Level" of handling qualities involved. This linkage can also be interpreted in terms of likelihood of survival or probability of kill for certain combat applications.

2. Quantification of Task or Maneuver Performance

There is little or no documentation of task or maneuver performance details. Thus we have little understanding of how aggressively or precisely evaluation pilots performed tasks and thereby assigned ratings. Traditionally much is left to the judgment of the pilot in determining how a flight task is executed, but this may be an unfair burden when subtle variations in task performance can dramatically alter pilot workload. One simply must question the ability of the pilot to perform incisive self-analysis when performing difficult, demanding tasks.

3. Attention to Higher-Order Vehicle Dynamics

Another factor not adequately explored thus far is rotor flapping effects or second-order dynamic models in connection with helicopter roll control. In general, equivalent rigid-body roll damping has been assumed even though coupling with flapping modes is likely. Also, low-frequency dihedral effects can sometimes affect the pilot opinion, and these have not been examined.

One of the main features distinguishing rotorcraft from conventional aircraft is the slow effective actuator response related to the time to change tip-path-plane orientation. This is typically about 0.1 sec for a helicopter compared to about one-third that amount for conventional aircraft. Furthermore, this effective actuation time can be in addition to an actual hydraulic actuation time.

The rotor response also couples with the basic rigid body response in a way which alters the effective roll-due-to-cyclic transfer function form from first-order to second-order (or greater).

4. Distinction of Handling Qualities Elements

There has been sometimes poor distinction made of short-term response, control power, and control sensitivity issues in experimental results. Research during this program has brought to light the naturally-occurring confusion over these characteristics experienced by even highly qualified research pilots and engineers.

Also one can see in the literature that roll-axis handling qualities research results have been expressed in terms of many metrics. A feature such as short-term response is commonly expressed as roll damping, bandwidth, rise time, and exponential time constant. Control sensitivity can be put in terms of either roll rate or roll acceleration with respect to either force or deflection of lateral cyclic. Likewise, control power can be expressed as roll rate, acceleration, or maximum roll angle. Further confusion occurs when features such as control power and short-term response are combined in parameters such as time to a given bank angle or bank angle in a given time.

Thus there is good reason for the variation in handling qualities results obtained thus far. The multitude of tasks, maneuvers, metrics, and dynamic features simply confounds the careful measurement and analysis of handling qualities. Of course this observation can be applied to all axes of control, not just the roll axis.

B. Research Objectives

This basic objective of this study is to provide handling qualities criteria for the design of roll control effectiveness in military rotorcraft. The data obtained and analysis performed is for use in the current update of MIL-H-8501A, the handling qualities specification for helicopters.

Special attention is given to the reasons for dispersion in experimental results as mentioned above. Where possible, experiments are designed to expose variables resulting from the task, vehicle, and pilot characteristics.

1. Establishment of Task Dependence

First, there is an effort to establish criteria which are rationally dependent on the tasks which must be performed to accomplish given design missions. This involves understanding how tasks are performed and how they should be measured.

Thus there is an objective to emerge from this research program with specific methods for measuring task performance as it relates to and influences handling requirements. Moreover, it is desired to establish in explicit, rational terms how handling qualities support and ensure given levels of mission performance.

2. Orthogonality of Criteria

Second, criteria are used, or developed where needed, which are suitably orthogonal. That is, careful distinctions are made among the individual features such as short-term response, control power, and control sensitivity.

Satisfaction of this objective is believed to be of considerable use in structuring of handling qualities specifications.

3. Consideration of Existing Criteria

Finally, specific criteria offered here are discussed and compared to previous counterparts in order to make use of past design decisions and to generalize other data.

It is recognized that there have been a substantial number of studies and experimental efforts conducted to establish handling qualities criteria. Although some of these results conflict or have been interpreted in a variety of terms, there is nevertheless considerable validity insofar as the original assumptions and experimental conditions are known.

C. Report Organization

The following sections of this report include a description of the technical approach taken, experimental results, analysis

and development of design criteria, and resulting conclusions and recommendations.

1. Technical Approach

The technical approach is described in terms of each of the three elements of handling qualities: pilot, vehicle, and task. For each of these elements, individually and combined, the important factors are listed, quantified, and discussed.

One emphasis of the technical approach is the importance of the flight task or maneuver in dictating specific handling qualities requirements.

2. Simulator Program

The experimental simulator program is described in terms of equipment and procedures used. The factors which define experimental limitations are defined.

Again, task dependence and the necessity of quantifying task or maneuver performance is stressed in the description of the simulator program.

3. Experimental Results

The experimental results of the simulator program are described according to the handling qualities components investigated: control power, short-term response, and control sensitivity.

This report will summarize results already reported in Reference 3, and will go on to discuss subsequent work. This is intended to be an overall program summary document covering the general subject of helicopter roll control effectiveness criteria.

4. Criteria Development and Analysis

The criteria development process is described, first in general terms, then according to the individual handling qualities components involved.

5. Conclusions and Recommendations

In addition to basic handling qualities, conclusions and recommendations will cover the general use of simulation and the topic of mission/flight task quantification.

II. TECHNICAL APPROACH

The technical approach taken here emphasizes the task being considered and the rational direct quantification of that task. This is regarded as the main factor which distinguishes this study from previous ones in which similar handling qualities issues have been examined.

A. Pilot-Vehicle-Task Interaction

The study of handling qualities demands that one choose carefully the parameters to study both analytically and experimentally. Further, these parameters involve not only the vehicle, but also the pilot and task. The following is a description of how these system parameters were selected for this study.

One convenient way to portray the relationship among pilot, vehicle, and task is shown in Figure 2. Note that the task is viewed as the specific context in which the pilot and vehicle operate. Of course a major feature is the closed-loop relationship between pilot and vehicle.

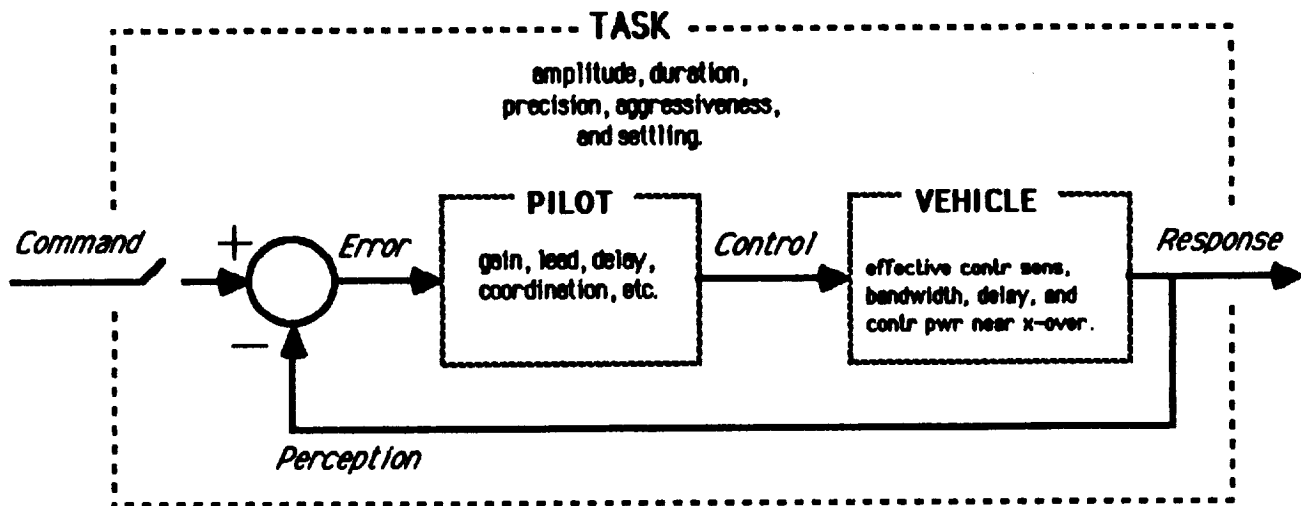


Figure 2. Pilot-Vehicle-Task System Block Diagram.

The technical approach taken here involves the partitioning of vehicle and task components in analogous and compatible terms. There is of course a traditional and well accepted taxonomy for vehicle characteristics, including such factors as control power, control sensitivity, response time, damping, and others. There

is less of a precedent for task characteristics because the task is not often quantified or considered in terms other than a simple label.

The key idea of the technical approach is this. If the dynamic requirements of individual tasks can be understood and quantified, then one can go far in establishing the vehicle response needed to fulfill those task requirements. That is, the task represents the operating context of the pilot and aircraft. Quantitative definition of that context in turn defines the needed vehicle response characteristics.

As an example, suppose the representative level of aggressiveness of a lateral unmask/remask maneuver is determined. It is then possible to find the specific amount of vehicle quickness (short-term response) which will enable the human pilot to perform with the required aggressiveness but with acceptable workload. In other words, the vehicle response requirements can be tailored to specific task demands.

This concept thus permits flexibility in design requirements depending upon the intended missions and tasks within those missions. Thus it is feasible to set rational design criteria for a scout/attack helicopter in contrast to, say, a cargo helicopter.

Further, there is the potential for establishing handling qualities based on mission performance factors. Thus handling qualities could be related not just to workload but also to whether a successful mission can be performed. This gives handling qualities a clearer role in the overall design scheme.

B. Task Dynamics

If the task is looked on as simply the total pilot-vehicle combination, i. e., the closed-loop system, then one can carry along conventional dynamic system notions for the task. These include such features as quickness of response, damping or settling, precision, amplitude of motion, and others.

In this study a taxonomy of task parameters was evolved and refined during simulator experiments. The net result was to demonstrate a parallel manner of addressing both task and vehicle elements. A basic list of task features and parameters is given in Table 1.

Table 1. List of Quantifiable Task Parameters.

Feature	Meaning
Amplitude	amount of motion or displacement
Aggressiveness	specific quickness of performance
Precision	nearness to performance standards
Settling	damping or lack of oscillation
Duration	total time required to accomplish task

Each of these features can be viewed as the effective closed-loop system characteristics of the pilot-vehicle combination. The following is a brief definition and discussion of each task feature.

1. Amplitude

Amplitude refers to how large the maneuver in terms of motion or control movement. For example the amplitude of a commanded heading change in an IFR operating environment would clearly involve a much smaller amplitude bank angle change or roll rate than, say, for an aggressive air combat maneuvering task. Typically the former would be limited to bank angles of 15 deg or less while the latter could involve bank angles in excess of 75 deg.

More than one state variable could be used to define maneuver amplitude. For the roll axis, both attitude and roll rate are logical candidates. Others could be considered, including normal acceleration, control deflection, and control force.

2. Aggressiveness

Aggressiveness is the effective measure of quickness in doing a task. This could involve various forms of "rise time" or bandwidth metrics.

The typical concept of aggressiveness involves how "tightly" the pilot is tracking or performing a maneuver. This might be set by the "aggressiveness" of the command (e. g., an evading target) or the pilot's own sense of urgency in accomplishing the task.

While aggressiveness can be closely related to task duration, there may be an important distinction necessary. This will be discussed below.

3. Precision

Precision is how closely the pilot achieves a predetermined task variable value and is a commonly used metric for task performance. As with other features, precision can be measured in a number of ways. The operational precision will depend upon the pilot and what form of information is available. Explicit distances or angles are generally not available unless specifically displayed.

Often the degree of precision obtainable is dependent upon the amount of aggressiveness, maneuver amplitude, or the vehicle dynamics involved. Precision is usually gained only at the cost of these other task performance features.

4. Settling or Damping

Settling refers to how effectively a commanded maneuver is accomplished in terms of overshoot or residual oscillation. In a very real way, settling is represented as a damping ratio of the closed-loop pilot-vehicle system. Thus this feature can be closely related to "phase margin."

In general, the amount of overshoot is less in the outer-loop task performance features (control of position) than for inner-loop ones (attitudes). This is presumably due to the fact that the ultimate task objectives are more closely associated with outer-loop aspects and these can often be achieved with relatively unsettled regulation of attitude.

One example of the above can be seen in the matched landing flare performance for a conventional aircraft (an outer-loop task). Reference 9 shows that the effective closed-loop damping ratio in such a task is about 0.7 to 0.9. Data describing inner-loop control (e. g., Reference 10) indicates that control of attitudes involves closed-loop damping ratios of about 0.3 (about a 30 deg phase margin).

5. Duration or Time-Available

Duration is the amount of time available to complete a task or maneuver prior to beginning another. Thus it involves a composite of the rise-time (aggressiveness) and settling to a given level of precision. Further, the task duration can include

a dwell time during which there is no action by the pilot, or the completion of certain secondary tasks.

In contrast to the time available (a task feature), the time required to perform a task depends upon the vehicle and pilot and their associated limitations. The ratio of time available to time required is a strong factor in the "time-loading" aspect of workload.

C. Vehicle Dynamics

As mentioned earlier, vehicle dynamics can be expressed in a number of ways. For the purpose of this study, the following set of vehicle equations has been found particularly useful for understanding the physics involved and ultimately developing rational vehicle-centered criteria for handling qualities.

The basic helicopter equations of motion for the roll axis are expressed in Table 2. Note that these include the tip-path-plane flapping motion, the fuselage-rotor hub moment, and the fuselage side force. A total of three degrees of freedom are included in the fourth-order system dynamics.

Referring to the matrix form in Table 2, note that there are three vehicle characteristics involved in the equations of motion. These are:

(i) Flapping stiffness, L_{b_1} ,

(ii) Tip-path-plane lag, τ_b ,

and (iii) Dihedral effect, db_1/dv .

It will be shown shortly that both the tip-path-plane lag and dihedral effect do not vary substantially from one helicopter to another. However the flapping stiffness does and thus is of particular importance to this study and to the matter of handling qualities, in general. Figure 3 illustrates the range of flapping stiffness for several designs spanning a large range of gross weight and size.

Several approximate factor relationships are given in Table 3. These are useful in relating the vehicle dynamics to handling qualities features.

Table 2. Summary of Helicopter Equations of Motion.

Equations of Motion

$$\tau_b (\dot{b}_1 + p - p_g) + b_1 + \frac{\partial b_1}{\partial v} (v - v_g) = A_1 \quad (\text{first-order flapping})$$

$$\dot{p} = L_{b_1} b_1 \quad (\text{hub moment})$$

$$\dot{v} = g (\delta + b_1) \quad (\text{side-force})$$

Note: Subscript g refers to gust velocities.

Matrix Form

$$\begin{bmatrix} (\tau_b s + 1) & \tau_b & \frac{\partial b_1}{\partial v} \\ -L_{b_1} & s & 0 \\ -g & -g/s & s \end{bmatrix} \begin{bmatrix} b_1 \\ p \\ v \end{bmatrix} = \begin{bmatrix} 1 & \tau_b & \frac{\partial b_1}{\partial v} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} A_1 \\ p_g \\ v_g \end{bmatrix}$$

Expanded Polynomials

$$\Delta = s^4 + 1/\tau_b s^3 + (L_{b_1} - \frac{g \partial b_1}{\tau_b \partial v}) s^2 + L_{b_1} \frac{g \partial b_1}{\tau_b \partial v} \quad (\text{denominator})$$

$$N_{A_1}^p = L_{b_1}/\tau_b s^2 \quad (\text{roll rate to lateral swashplate numerator})$$

$$N_{A_1}^{b_1} = 1/\tau_b s^3 \quad (\text{lateral flapping to lateral swashplate numerator})$$

$$N_{A_1}^v = \frac{g}{\tau_b} (s^2 + L_{b_1}) \quad (\text{side-velocity to lateral swashplate numerator})$$

Transfer Function

$$\frac{\delta}{A_1}(s) = \frac{L_{b_1}/\tau_b s}{[s^2 + 1/\tau_b s + L_{b_1}] [s^2 + \frac{g \partial b_1}{\tau_b \partial v}]} \quad (\text{bank-to-lateral swashplate})$$

Table 2. (concluded) Summary of Helicopter Equations of Motion.

Stability Derivatives

$$1/\tau_b = \frac{\gamma\Omega}{16} \left(1 - \frac{8e}{3R}\right) \quad (\text{Tip-path-plane inverse lag})$$

$$L_{b1} = L_{b1}^{(t)} + L_{b1}^{(h)} + L_{b1}^{(s)} \quad (\text{Total flapping stiffness})$$

$$L_{b1}^{(t)} = \frac{Th_c}{I_x} \left(1 + \frac{\dot{h}}{\Omega R} \frac{8C_T}{\sigma\sigma}\right) \quad (\text{Thrust relative to cg})$$

$$L_{b1}^{(h)} = \frac{b M_B \Omega^2 e}{2 I_x} \quad (\text{Hinge offset})$$

$$L_{b1}^{(s)} = \frac{b K_B}{2 I_x} \quad (\text{Flapping spring})$$

$$\frac{\partial b_1}{\partial v} = \frac{2}{\Omega R} \sqrt{\frac{8C_T}{\sigma\sigma} + \sqrt{\frac{C_T}{2}}} \quad (\text{Dihedral effect})$$

Roll Response Parameters

- A_1 • Lateral swashplate angle
- a • Blade lift-curve-slope
- b • Number of blades
- C_T • Thrust coefficient, $\frac{T}{\rho\pi R^2(\Omega R)^2}$
- c • Blade chord
- e • Flapping hinge offset
- g • Gravity constant
- h_r • Height of hub above cg
- \dot{h} • Vertical velocity
- I_x • Helicopter roll inertia
- I_B • Blade flapping inertia
- K_B • Blade flapping spring
- L_{b1} • Blade flapping stiffness
- M_B • Blade flapping mass moment
- p • Roll rate
- R • Rotor radius
- s • Laplace operator
- T • Thrust
- W • Gross weight $\frac{\rho ac R^4}{I_B}$
- γ • Lock number, $\frac{\rho ac R^4}{I_B}$
- ρ • Air density
- σ • Solidity ratio, $\frac{bc}{\pi R}$
- τ_b • Tip-path-plane lag
- θ • Roll attitude
- Ω • Rotor angular velocity

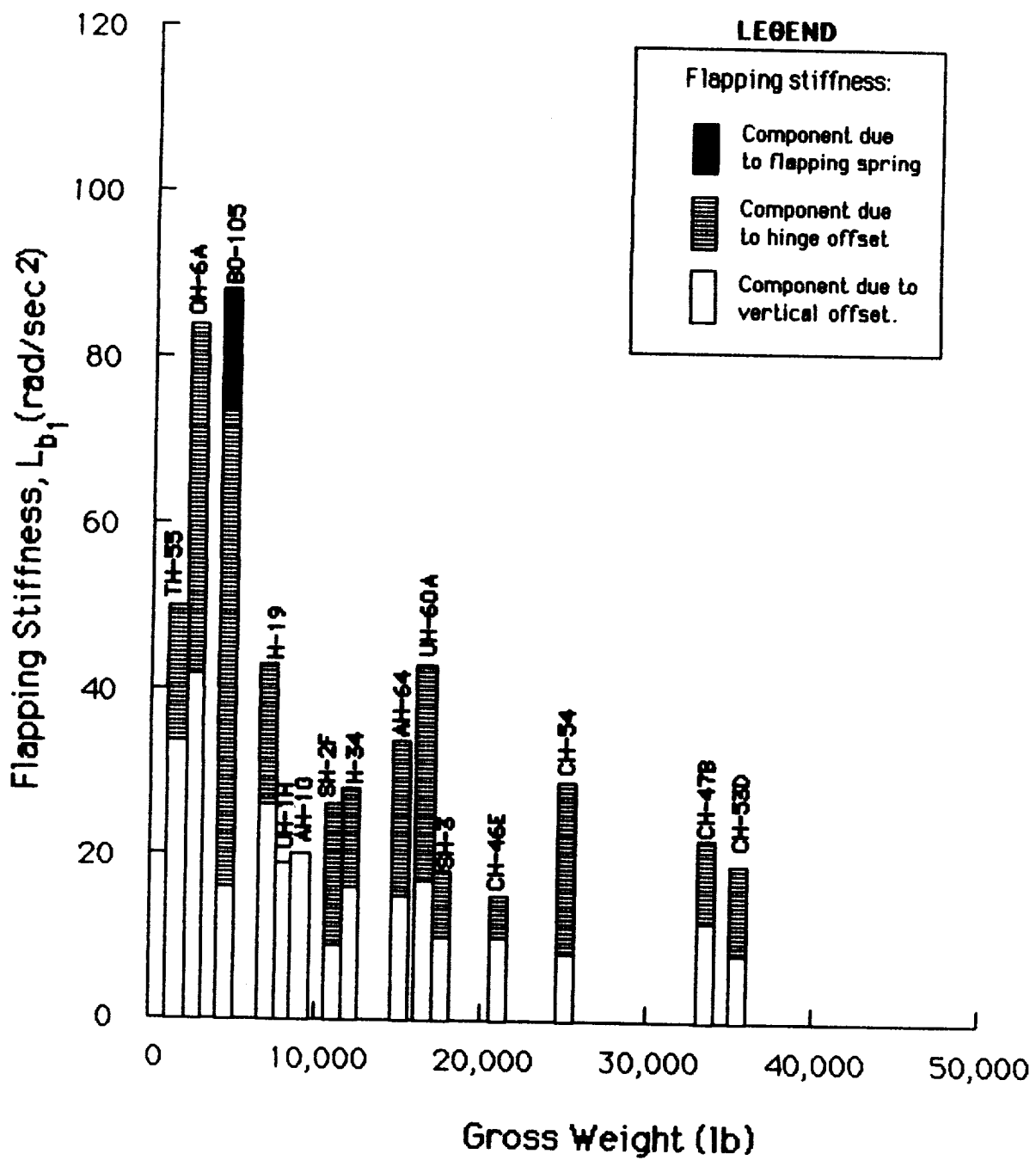


Figure 3. Flapping Stiffness Characteristics for Several Designs.

Table 3. Approximate Factors for Roll-Axis Dynamics.

a. High-frequency approximate factors:

$$\frac{p}{A_1} \approx \frac{L_{b_1}/\tau_b}{[s^2 + 1/\tau_b s + L_{b_1}]}$$

$$\text{Tip path plane lag, } \tau_b \approx \frac{16}{\gamma \Omega}$$

$$\text{Second-order roll response natural frequency} \approx \sqrt{L_{b_1}}$$

$$\text{Effective roll damping, } L_p \approx -L_{b_1} \tau_b$$

$$\text{Effective roll time constant, } T_R \approx -1/L_p$$

$$\text{Bandwidth for 45° phase margin, } \omega_{bw} \approx \sqrt{L_{b_1} + \left(\frac{1}{2\tau_b}\right)^2} - \frac{1}{2\tau_b}$$

b. Low-frequency approximate factors:

$$\frac{g}{A_1} \approx \frac{1/\tau_b s}{[s^2 + \frac{g}{\tau_b} \frac{\partial b_1}{\partial v}]}$$

$$\text{Frequency of lateral phugoid} \approx \sqrt{\frac{g}{\tau_b} \frac{\partial b_1}{\partial v}}$$

$$\text{Damping of lateral phugoid} \approx 0$$

c. Control-power approximate factors:

$$\text{Acceleration } \frac{\ddot{b}}{A_1} \approx L_{b_1} \quad \text{for } 1/T_R < \omega < 1/\tau_b$$

$$\text{Roll rate } \frac{p}{A_1} \approx \frac{1}{\tau_b} \quad \text{for } \omega < 1/T_R$$

$$\text{Trim } \frac{\int g dt}{A_1} \approx \frac{1}{g} \frac{\partial b_1}{\partial v} \quad \text{for } \omega < \sqrt{\frac{g}{\tau_b} \frac{\partial b_1}{\partial v}}$$

1. Control Power

The feature of control power can be expressed in several ways. The possible choices and preferences with regard to handling qualities application will be discussed later in Section V. Notable alternatives involve roll attitude, roll rate, and roll acceleration, each as functions of control force or deflection.

Another important dimension of control power is the degree of transience or the frequency-response aspect. The degree of control power in the short-term can appear quite different from the longer term. This is strongly related to the dynamic response properties.

An important control power relationship is the amount of roll rate which can be generated for a given swashplate deflection. This also happens to be related to the effective tip-path-plane lag. The governing equation is:

$$\frac{dp}{dA_1} = \frac{\gamma \Omega}{16}$$

where γ is the Lock Number,

and Ω is the rotor angular velocity.

The effective rotor tip-path-plane lag is the inverse of this quantity. Since the product of Lock Number and rotor rpm is fairly constant (a value of about 220) the effective lag remains in a fairly narrow range (about 0.7 to 1.0 sec). Thus the factor which really sets the amount of roll rate capability is simply the swashplate deflection range. The roll rate available, of course, is reduced by roll rate augmentation unless it is washed out within the span of a given maneuver.

Another factor involved in control power is the "dihedral effect" wherein there is a rolling moment attenuation proportional to the side velocity developed. This can be expressed in terms of the lateral flapping angle produced by a side velocity component, or:

$$\frac{db_1}{dv} = \frac{2}{\Omega R} \sqrt{\frac{8 C_T}{a \sigma} + \sqrt{\frac{C_T}{2}}}$$

Hence, the dihedral effect is a function of thrust coefficient, which can vary. But the effect in terms of the low frequency hover cubic natural frequency (the phugoid-like motion) is actually fairly invariant and will be found to be about 0.5 rad/sec for most designs.

2. Short-Term Response

Short-term response also can be expressed in a number of ways, both in the time- and frequency-domains.

Using the form defined in Table 3 above, the most direct parameter is lateral flapping stiffness, L_{b_1} . As shown earlier in Table 2, this is equal to the square of the natural frequency for the combined rotor-body rolling mode.

Another common measure of short-term response is the effective roll damping, sometimes expressed as the dimensional stability derivative L_p . While this has more physical significance for a conventional rigid-body aircraft, the equivalent for a helicopter can be computed using the product of flapping stiffness and effective tip-path-plane lag time constant. Recalling that the latter is fairly invariant, the roll damping, L_p , is thus essentially proportional to the flapping stiffness, L_{b_1} .

A comprehensive description of short-term response dependence on vehicle design characteristics is given in Reference 10.

3. Control Sensitivity

Control sensitivity, like control power, can be represented in several ways. While sensitivity is essentially just the ratio of a motion change to a control change, there are a number of alternatives for each quantity.

Motion can be defined in terms of roll acceleration, angular velocity, or roll attitude change. Control input can be either manipulator applied force or deflection. Finally the ratio itself can be expressed as a total change, local slope, or as a frequency response rather than a static change.

If roll control sensitivity is represented by the partial derivative of roll rate with respect to lateral swashplate deflection, then the above control power relationship involving Lock Number and rotor rpm governs. If control power is based on lateral cyclic deflection, then control gearing enters.

4. Cross Coupling

While cross coupling is not of primary interest in this study, it is worthwhile considering in the same context as the above parameters. Again, it can be represented in many ways. Some alternatives are discussed in Reference 11.

One important distinction is whether cross-coupling occurs due to control input, inertial properties, or aerodynamics. An example of the first is yaw due to collective pitch change. The

second typically arises from misalignment of principal axes and the preferred control axis and might include yaw due to roll. The final type can arise from a number of complex aerodynamic factors, including tip-path-plane dynamics and aerodynamically coupled hub moments. Each varies in terms of how easily the pilot can compensate or decouple the unwanted response.

D. Pilot Dynamics

Pilot control strategy or technique has a role in handling qualities as expressed by the closed-loop pilot-vehicle-task block diagram presented earlier. However, explicit definition of the pilot model must be avoided if possible because of the likely pilot-to-pilot variation in technique and use of cues. Fortunately it is sufficient to assume that the individual pilot does what is necessary in order to extract a given level of closed-loop performance from a given vehicle configuration. In effect, we are recognizing that quantification of the pilot is redundant if we have already quantified the vehicle and the task dynamics (where task includes the closed-loop pilot-vehicle combination).

Even though we choose to avoid explicit quantification of pilot dynamics in this study, it is nevertheless useful to list the elements involved in pilot actions. The various features of the pilot are shown in Figure 4. Each is discussed in detail in the following paragraphs.

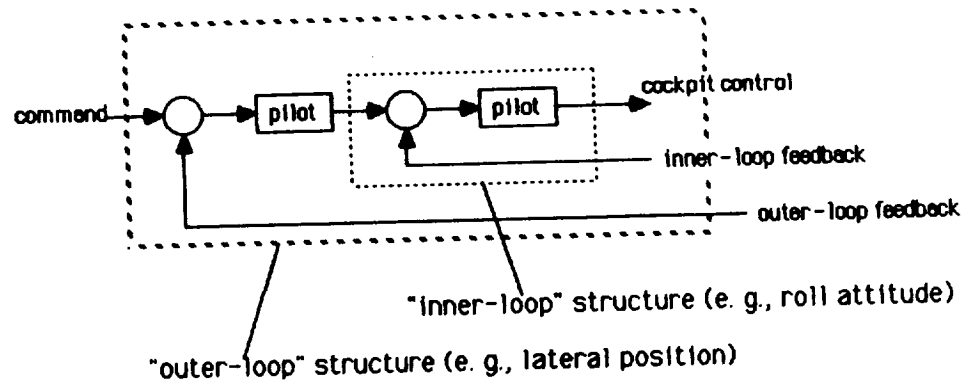
1. Loop Structure

Basic pilot technique is often expressed as loop structure. This is the basic way in which the pilot's resources are organized in order to carry out a given task or maneuver.

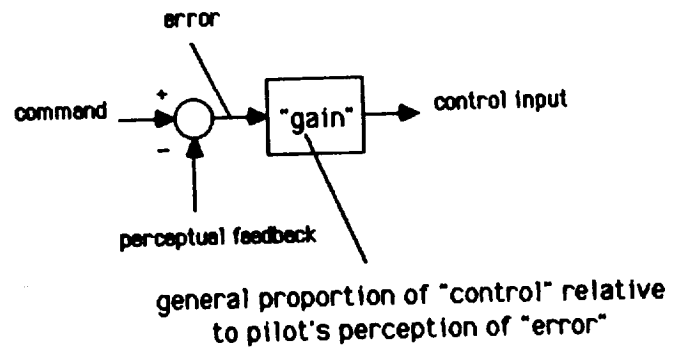
The most fundamental aspect of loop structure is its organization as a parallel or series set of "inner-" and "outer-loops." Typically most lateral flight tasks or maneuvers need to be represented by a series structure in which the inner-loop is comprised of bank angle command and control, and the outer-loop involves either heading or lateral position.

Another facet of loop structure is the degree to which either or both loops are being closed in a continuous or sample-data fashion. Examined on a microscale, all pilot behavior is probably best represented as a sample-data system. However, it is no doubt adequate to treat inner-loop behavior as essentially continuous when treating the overall inner- and outer-loop system as a whole.

Loop Structure:



Loop Gain:



Compensation:

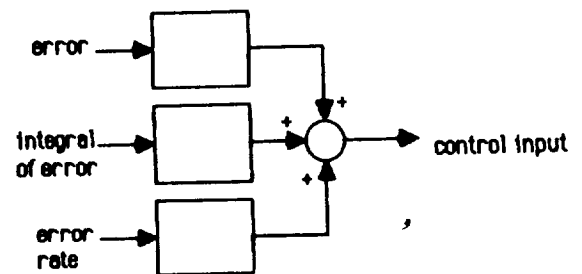


Figure 4. Elements of the Pilot.

2. Loop Gain

The pilot loop gain describes how tightly the pilot tries to apply control inputs as a function of the desired and perceived results.

In general, the combination of loop gain and control sensitivity set the level of aggressiveness of the task or maneuver being performed.

The most relevant measure of loop gain is the "crossover frequency" because it normalizes the control and motion quantities involved in closed-loop actions.

3. Compensation

Pilot compensation can refer to a number of features, but most often it is associated with "lead" compensation, the feedback or generation of rate information in order to enhance closed-loop damping of the total system.

There needs to be some distinction made, however, in how lead compensation is generated. If lead is obtained by the pilot mentally computing rate information, then there can be a substantial workload penalty. On the other hand, if rate information is available explicitly, then it can be used by the pilot without the same mental workload. Unfortunately there is insufficient background data on how to weight such distinctions.

There should also be some note of artificially generated compensation such as provided by flight directors. Here the pilot relies heavily on a display quantity which may be very abstract compared to real-world states. This is an extreme form of compensation requiring little or no mental workload.

4. Coordination

Pilot coordination refers to the blending of control inputs in order to enhance response or to suppress cross coupling. Typical lateral coordination consists of a learned blend of lateral cyclic and rudder pedal in order to perform a turn with minimal lateral acceleration. At the same time, a skilled pilot coordinates lateral and longitudinal cyclic to maintain altitude under forward-flight conditions.

Other important aspects of coordination involve directional control to offset collective inputs and control in all axes to compensate for the basic asymmetry found in helicopters due to a single direction of rotation of the main rotor.

5. Delay

A major feature of the pilot is the effective transport delay which can arise from both basic neuromuscular lag and delays in perception.

Neuromuscular delay has been measured and found to have values ranging from 0.1 to 0.3 sec, depending upon the vehicle and the amount of lead compensation generated.

Perceptual delays can arise from several sources, including the basic control structure used, visual display dynamics, and the sampling rate of the pilot.

6. Time Sharing

An important aspect of the pilot is how several tasks are managed at once. This involves a time-sharing function in which two or three control axes may be handled sequentially, or possibly all at one time.

Time sharing can also involve attention to cognitive tasks such as communication and flight management. In general, these require a fair degree of unattended operation following basic control tasks.

III. SIMULATOR PROGRAM

A two-part simulator experimental program was conducted as well as some limited flight opportunities. Data were collected to support the general technical approach and to provide basic data from which to formulate criteria.

The two primary objectives of each simulator experiment were (i) roll control power data and (ii) short-term response data. In addition important data were collected with regard to roll control sensitivity and flight control system response type.

One part of the simulator program was to explore mission- or task-dependent aspects and to gain a better understanding of how to integrate these into handling qualities criteria. Perhaps the most notable example of this was the determination of time-loading factors in performance of several short-term discrete maneuvers. The result was to introduce an entirely new dimension to handling qualities than had been considered previously.

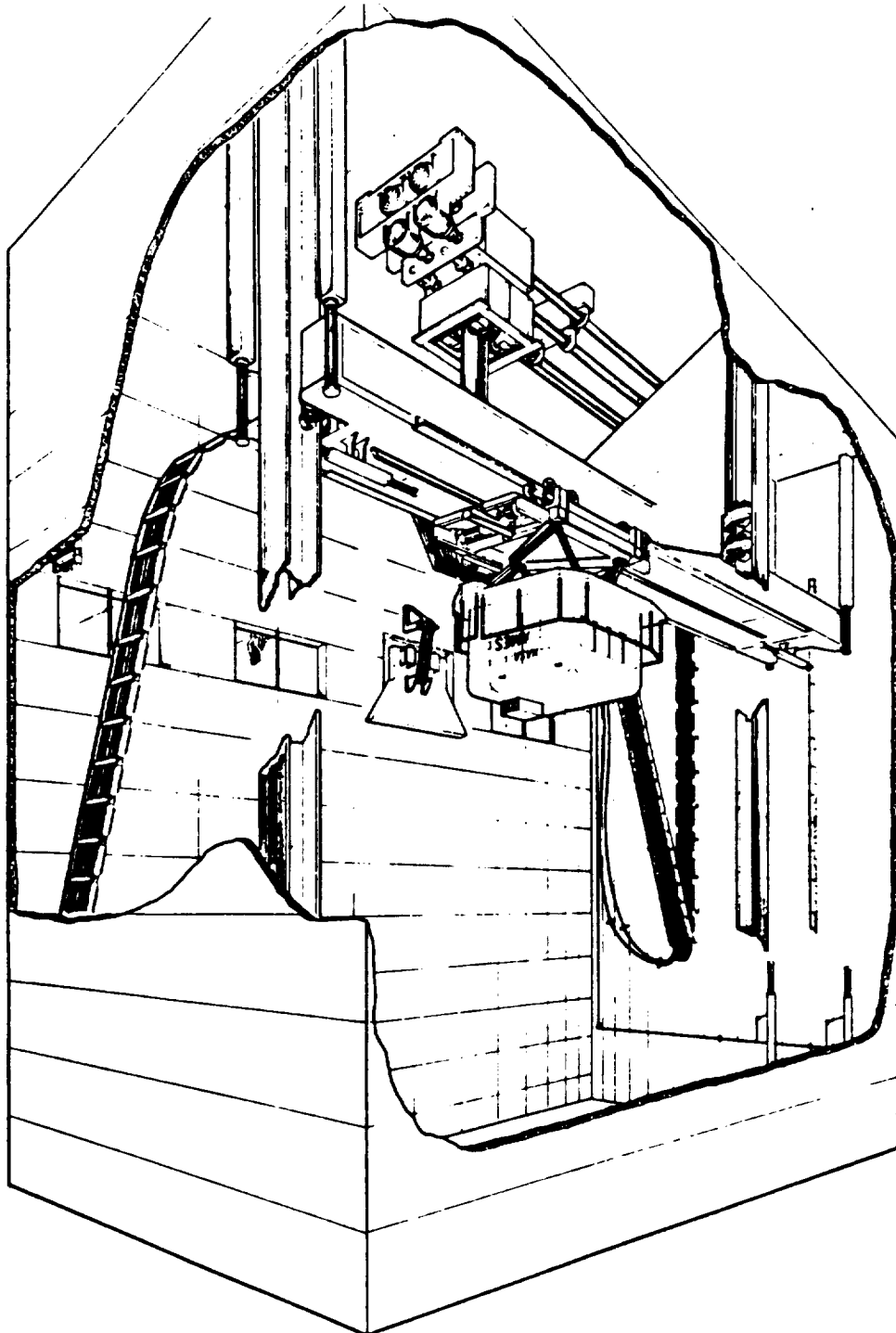
Early in 1984 two flights were made in order to record the performance of several maneuvers believed useful in assessing roll control effectiveness. These were performed at Crows Landing NALF 90 miles east of Ames Research Center using an instrumented UH-1H helicopter. Tasks included slaloms, rapid turns, and lateral sidesteps. The results of these flights were instrumental in choosing the tasks to be performed in the simulator and setting performance standards.

The simulator experiments were conducted in January 1985 and February 1986 at Ames Research Center. These involved a large number of subject pilots having a wide range of backgrounds and service experience.

A. Experimental Equipment

1. Simulator Apparatus

All simulator experiments were run on the NASA Ames large-amplitude Vertical Motion Simulator (VMS). The VMS system is illustrated in Figure 5.



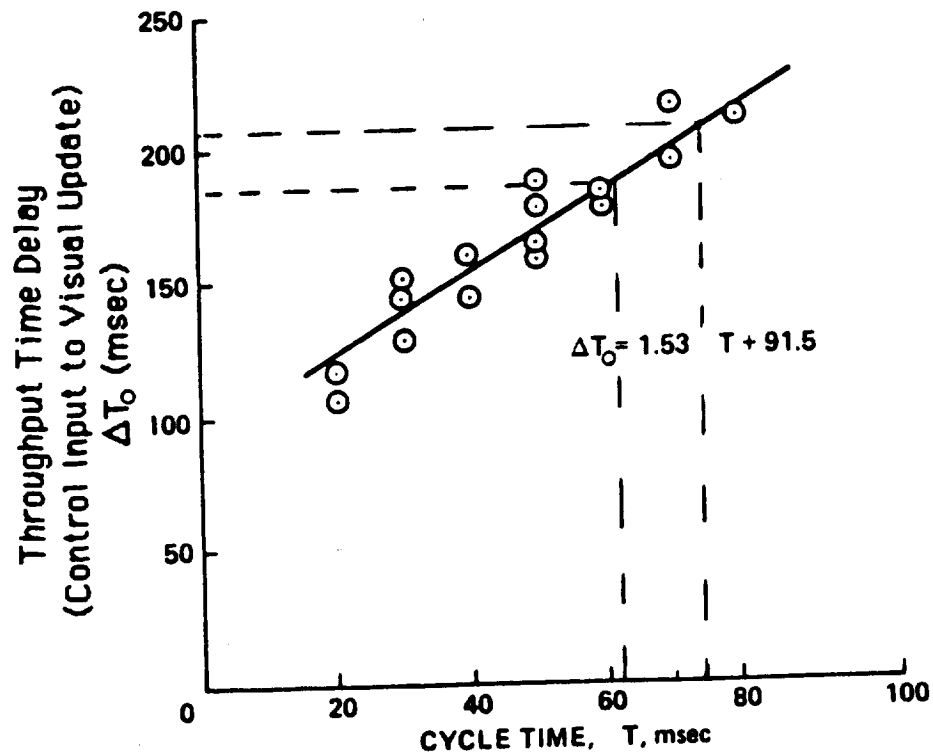


Figure 6. Effect of Host Computer Cycle Time on Throughput Delay (borrowed from Reference 12).

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2. Simulator computer

The choice of simulator computer was an important factor in the results obtained. The first set of experiments were run with the somewhat slow Xerox Sigma 8 general purpose (host) computer operating at about 70 msec frame time. The second set of experiments involved the CDC 7600 computer operating at about 25 msec, and in addition, an effective digital delay compensation filter cancelling most of the residual visual delay.

The slower host computer was found to preclude successful examination of short term response properties, but was adequate for exploring some control power requirements.

The digital delay compensation system was found particularly effective and was estimated to be capable of cancelling about 100 msec of throughput delay. The compensator as described in Ref 13 is known as a "twice-tuned extrapolation" algorithm and resides entirely in the host computer software. An alternative method which was implemented but not tested here is the SPAN filter described in Reference 14.

3. Vehicle Math Models

The helicopter airframe was represented using the ARMCOP model described in Reference 15. This model included second-order flapping and coning degrees of freedom.

The ARMCOP model was matched to a baseline configuration for each of the two simulation periods. During the first, a UH-60 Black Hawk facsimile was used as the baseline, and for the second period a Bell Model 249 AH-1 Cobra was used. These choices of specific aircraft were made only in the interest of obtaining current, well-checked math models. Individual characteristics were of minimal interest and important roll-axis characteristics were varied according to the experimental design.

Flight control systems were modeled to represent both augmented and unaugmented designs. Again, in order to maximize the operational usefulness of the simulator, an existing flight control system math model was used. In this case it was based on the Advanced Digital Optical Control System (ADOCS) design from Reference 16.

Three general types of control system configurations were used:

- (i) Unaugmented roll axis (roll damping provided aerodynamically or the equivalent) and a compatible level of pitch-axis damping via the flight control system.
- (ii) Roll-rate-command augmentation in the roll axis with a compatible pitch-axis flight control design.

- (iii) Bank-angle-command augmentation in the roll axis with a compatible pitch-axis flight control design.

In each case it was found necessary to provide a turn-coordination mode for forward flight in order to minimize an undesired tendency for the ARMCOP vehicle math model to diverge in airspeed and angle of sideslip. The ARMCOP difficulty was examined by several parties but no main cause was found for the sideslip problem.

4. Controls and Displays

Manipulators consisted of conventional center stick cyclic controls and separate collective. The issue of side stick controllers was not addressed.

A conventional array of helicopter cockpit instruments was provided, including engine torque indication. During the second simulation period the cockpit instruments were presented on a dedicated computer-generated imagery system. This was found acceptable by pilots and provided excellent flexibility for engineering graphics.

A head-up display was furnished for those tasks requiring it, namely, the HUD tracking and air combat tracking tasks. A description of the HUD format is given in Reference 3.

B. Experimental Procedure

1. Flight Tasks

A variety of flight tasks were run in order to explore the task dependence of lateral handling qualities. The various task explored are listed in Table 4.

Table 4. List of Lateral Control Flight Tasks Studied or Considered.

- Slalom around pylons located on both sides of a runway.
- Lateral jinking maneuver around simulated NOE obstacles.
- High-speed turns with respect to ground references.
- Lateral sidesteps from a hover condition.
- Cross-slope takeoff and landing.
- ATC-directed heading changes.
- Air combat maneuvers, particularly "scissors."
- Closed-loop continuous tracking task.

Ultimately this list was collapsed to three tasks on the basis of their relative importance, potential for revealing useful handling qualities information, and the ability to perform them on the VMS flight simulator facility. These three tasks included bank angle tracking of a HUD command bar, lateral side-step, and air combat tracking of a simulated target aircraft. The latter two tasks required the maximum visual and motion capability of the VMS system.

One task believed to be a critical design factor for lateral control power is the cross-slope takeoff and landing. This task was not pursued because of clear inadequacies in the simulator visual system and the need for a special vehicle math model.

The following is a detailed description of how each of the tasks were defined and flown by evaluation pilots.

HUD Tracking Task

The HUD tracking task was designed to induce large aggressive rolling maneuvers using a deterministic thus repeatable sequence of roll commands. The task was used as a part of both control power and short-term response experiments.

The HUD tracking task was conducted using a pseudo-random command of roll attitude through the display shown in Figure 7. The specific instructions given the pilot were to track commands aggressively in order to attain a precision of plus or minus 2 deg and to regulate loosely airspeed within 20 kt and altitude within 200 ft. The latter standards were intended to keep the vehicle dynamics essentially constant and attitudes within reasonable bounds

This task was considered to be essentially a single-axis task for the roll axis. That is there was no active regulation of heading, course, or track. Because of this, the task was considered a "laboratory" situation in which the pilot would likely exhibit limiting performance in terms of aggressiveness and precision. The task amplitude in terms of attitude changes was of course set by the HUD command and spanned a large range of values.

One specific function of the HUD tracking task was to examine whether a pilot tends toward a peak roll rate limit as bank angle changes take on very large values. This phenomenon had been observed in preliminary flight experiments but had not been examined under unrestrictive conditions such as are available in the simulator with a simple task such as this.

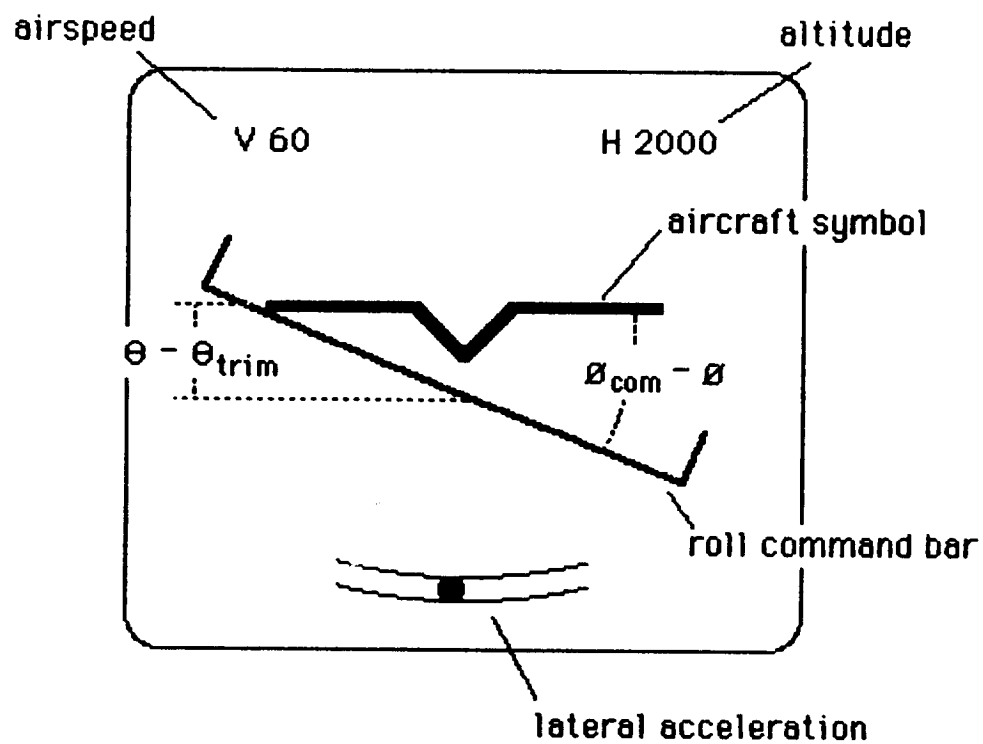


Figure 7. Display Used for HUD Roll Tracking Task.

Hover Sidestep Maneuver (Lateral Unmask/Remask)

Based on pre-simulation flight experience using a UH-1H aircraft, the hover sidestep maneuver was found to be an interesting, realistic task which precipitated both large amplitudes and reasonably aggressive behavior. The tactical counterpart of this task is the lateral unmask/remask maneuver wherein there is considerable pressure to minimize exposure during the movement from one position to the next.

The sidestep maneuver was performed along the side of a runway using adjacent rows of trees as the position reference. With the helicopter facing the trees and perpendicular to the runway, the pilot was requested to make an aggressive constant-heading sideward translation. The maneuver was ended when the helicopter was brought to a settled condition opposite the next tree in the line.

The two main variations in performing the maneuver were either to make a single translation from one tree to the next or to make a set of several sequential translations. The latter was used in conjunction with a time-loading procedure.

A description of the timed sidestep maneuver is given in Figure 8. The performance standards are described in that figure and were a crucial factor in determining successful execution of the maneuver.

It was found that one particularly crucial performance standard for this maneuver was the settling of roll attitude and roll rate at the end of a translation step. Without requiring settled attitude the pilot could still achieve the position precision even while sustaining a roll PIO. Such a condition would not, however, be of operational use as it would preclude transitioning to any subsequent task segment.

Preliminary simulator experience showed that this maneuver could not be done satisfactorily without reducing computer frame time and CGI delays. As a result, the most reliable results were obtained during the second VMS simulation experiment in which short-term response was the main topic studied and computer delays were minimal.

In addition, it was ultimately found that the cockpit controller must have good feel and response characteristics. During a short experiment subsequent to this study all the simulator features were carefully reproduced with one exception. This was the use of a side-stick controller with substantial stick filtering. It was not possible for the pilot to perform the rapid sidestep maneuver in this case and the controller characteristics were believed responsible.

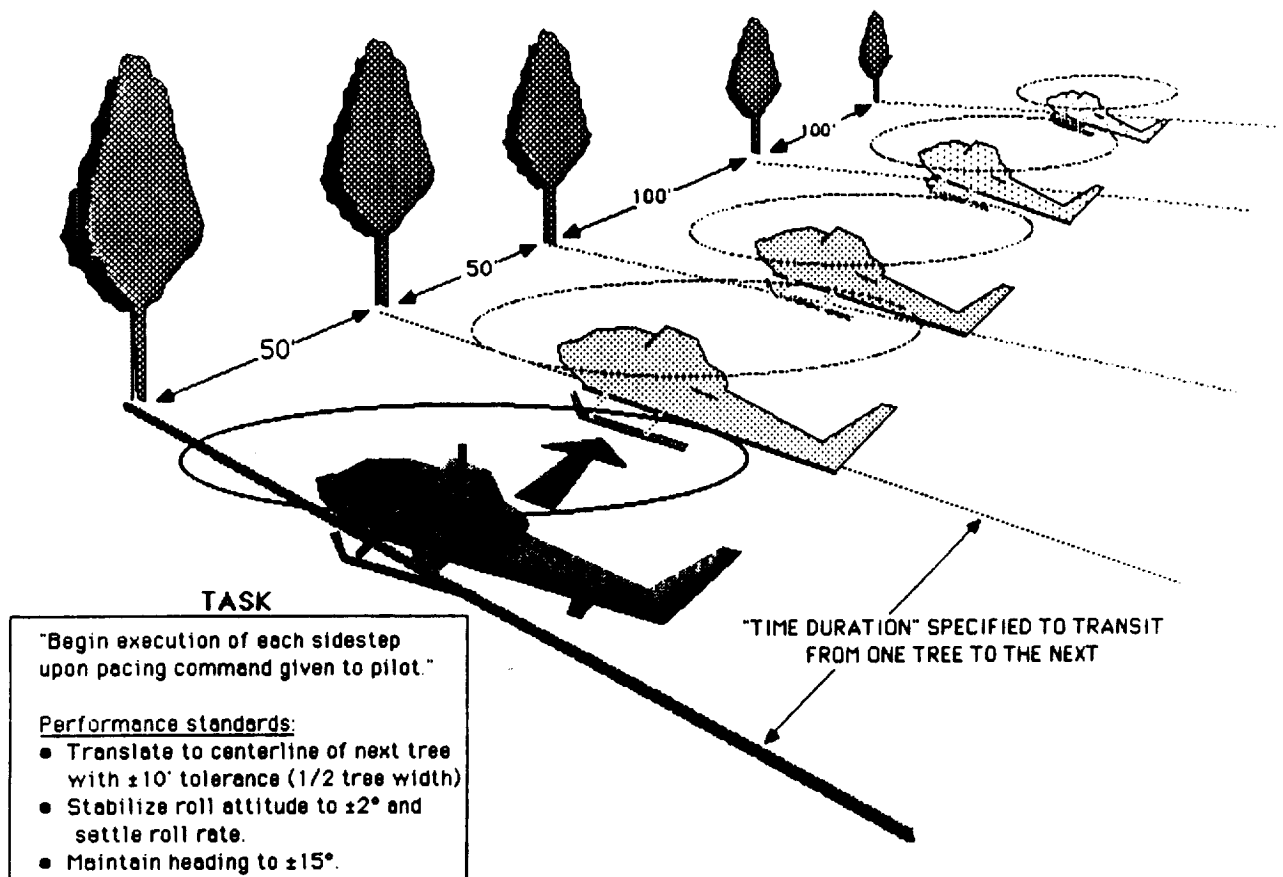


Figure 8. Sketch of the Timed Sidestep Maneuver.

Air Combat Tracking Task

A helicopter air combat maneuvering (ACM) task was simulated in order to examine the aggressive, large-amplitude rolling motions connected with tracking an evading target through a series of roll reversals. This task involved use of the Ames Helicopter Air Combat (HAC) simulation facility as described in Reference 17. The target consisted of a CGI display of a Soviet Hind helicopter as illustrated in Figure 9.

Various combinations of ACM conditions were tried in order to set the formal test procedure, including manual control of the target (red) helicopter, maneuvering in both vertical and horizontal planes, and use of ground obstacles and cover. It was found that in order to achieve a repeatable, well controlled experiment the target aircraft needed to be flown at constant speed and altitude through a series of programmed heading changes. The specific sequence of heading changes is shown in Table 5. A variation of this kind of maneuver is actually used by Army personnel involved in ACM training. Although the target aircraft trajectory was thus highly constrained and repetitious, pilots flying the attacking (blue) aircraft found the task demanding and realistic.

A head-up display was used for furnishing gun sight information during ACM. Various scoring parameters were recorded, but the time-on-target (within a plus or minus 2 deg) proved to be a useful guide for the pilot in determining the level of performance.

Range to the target was found to be by far the most important task variable determining pilot workload. While the pilot was never requested to maintain a specific target range, it was carefully noted and used in analyzing results. Some intentional variation in average range was induced by starting the pilot at differing distances and asking for range to be kept about the same. Results were then plotted based on the actual average range for a given run.

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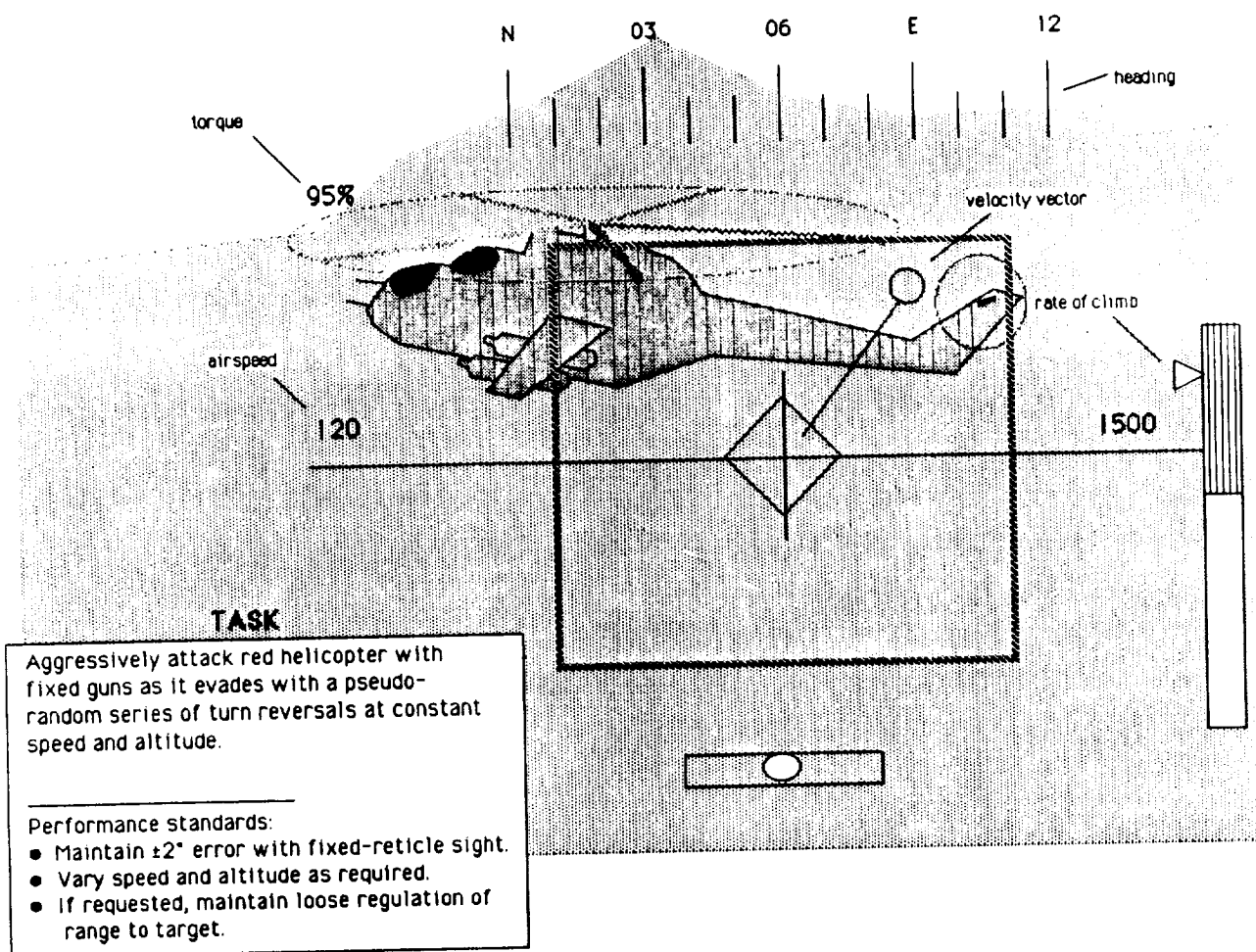


Figure 9. Sketch of the ACM Tracking Task.

Table 5. Air Combat Maneuver Heading Change Sequence.

At a heading of:	Bank to:
180 deg	45 deg R (right)
270	30 L (left)
195	40 R
315	45 L
255	20 R
300	40 L
210	20 R
225	60 R
045	45 L
225	level

Slalom Maneuver

The slalom maneuver was used in order to provide a tie-in with a number of existing flight and simulator data. A variety of slalom courses were considered, including the "U. S. slalom" described in Reference 18, the "German slalom" described in Reference 19, and combinations of rapid turns near the ground which are presented in Reference 3. In addition, the Reference 20 flight tasks involving low-level flight along terrain features such as streambeds and roads were also considered.

The specific slalom-like tasks actually flown during the simulation included a high-speed course around pylons placed at 1000 ft intervals along a runway centerline, a slower jinking maneuver around a 60' wide obstacle placed every 600', and abrupt turns performed at runway intersections through angles of 50 deg and 130 deg. Details of the slalom and turn maneuvers can be found in Reference 3.

IFR Heading Change Maneuver

The IFR heading change was a mild, unaggressive lateral maneuver. This was performed by the pilot responding in a normal manner to an ATC request for a given heading change. The pilot flew under simulated IMC conditions using basic flight instruments.

2. Pilot Rating Procedures

Pilot ratings were obtained using the standard Cooper-Harper handling qualities rating scale described in Reference 21 and described below in Figure 10. It was found necessary to define carefully all aspects of a task or maneuver in order to obtain precise, repeatable ratings from one run to the next and one pilot to the next. To accomplish this a checklist of task features was provided as a guide to recorded pilot commentary. This checklist is shown in Figure 11.

HANDLING QUALITIES RATING SCALE

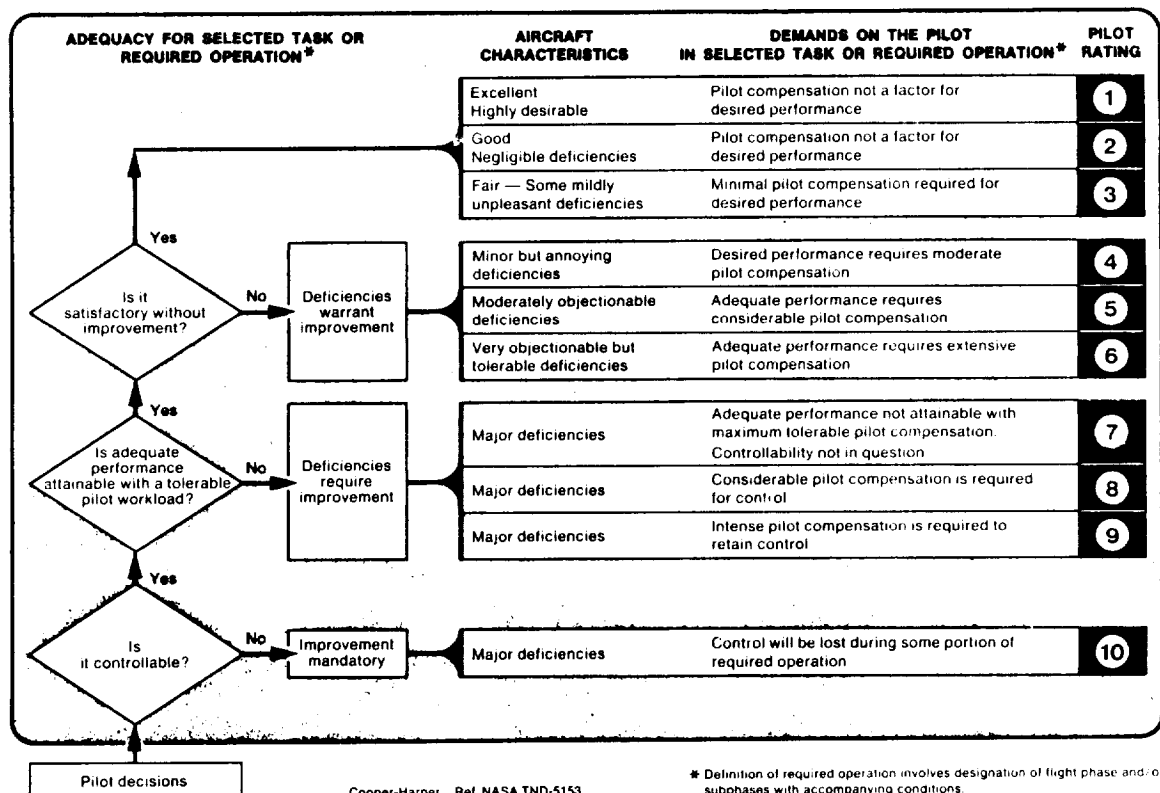


Figure 10. Cooper-Harper Rating Scale.

For the purpose of standardizing the information and instructions given to evaluation pilots, a formal pilot briefing package was assembled. This also included project background information, detailed task definitions, and evaluation procedures.

a. Pilot Commentary Checklist.

Task (or reqd operation*)	Technique (and demands on pilot*)	Configuration (a/c characteristics*)
1. Amplitude	1. Controls	1. Response time
2. Aggressiveness	2. Coordination	2. Controllability
3. Duration	3. Information	3. Control power
4. Precision	4. Compensation	4. Sensitivity

*These components are implicit in the Cooper-Harper rating scale.

Figure 11. Manudyne Pilot Commentary Checklist and Definitions.

b. Pilot Commentary Definitions.

Task

1. *Amplitude*: Size of correction or maneuver.
(e. g., how big a lateral error tolerated? bank angle error? ...)
2. *Aggressiveness*: Quickness or speed of task execution.
(e. g., how big a position correction?, bank?, other axes?, ...)
3. *Duration*: Time or distance elapsed between start and finish.
(e. g., how long to correct position?)
4. *Precision*: Fineness or exactness of task execution.
(e. g., how much lateral error is close enough?, ...)

Technique

1. *Controls*: Aircraft states or manipulators used to manage task.
(e. g., lateral cyclic for bank, bank for lateral position, ...)
2. *Coordination*: Combinations of controls and phasing needed.
(e. g., bank plus a little pedal, etc., ...)
3. *Information*: Displays and patterns needed.
(e. g., origin of streamers for flight path, heading for drift, ...)
4. *Compensation*: Anticipation or derivation of additional information.
(e. g., attention toward rate of change, anticipation, etc.)

Configuration

1. *Response time*: Lag, delay, period, rise time, etc.
(e. g., lag in bank before translation?, ...)
2. *Controllability*: Directness of control, washout, non-linearity, etc., ...
3. *Control power*: Absolute amount of response available.
(e. g., ability to make a large roll change, large rate, ...)
4. *Control sensitivity*: Amount of control pressure or deflection needed for reasonable motion and control harmony.

Figure 11. Manudyne Pilot Commentary Checklist, concluded.

Task performance was examined in terms of certain "discrete-maneuver" features which indicated both the magnitude and aggressiveness of the task. This was accomplished through time histories and phase-plane plots. The results for each were summarized in terms of the peak roll rate and net bank angle change. The general analysis procedure is outlined in Figure 12.

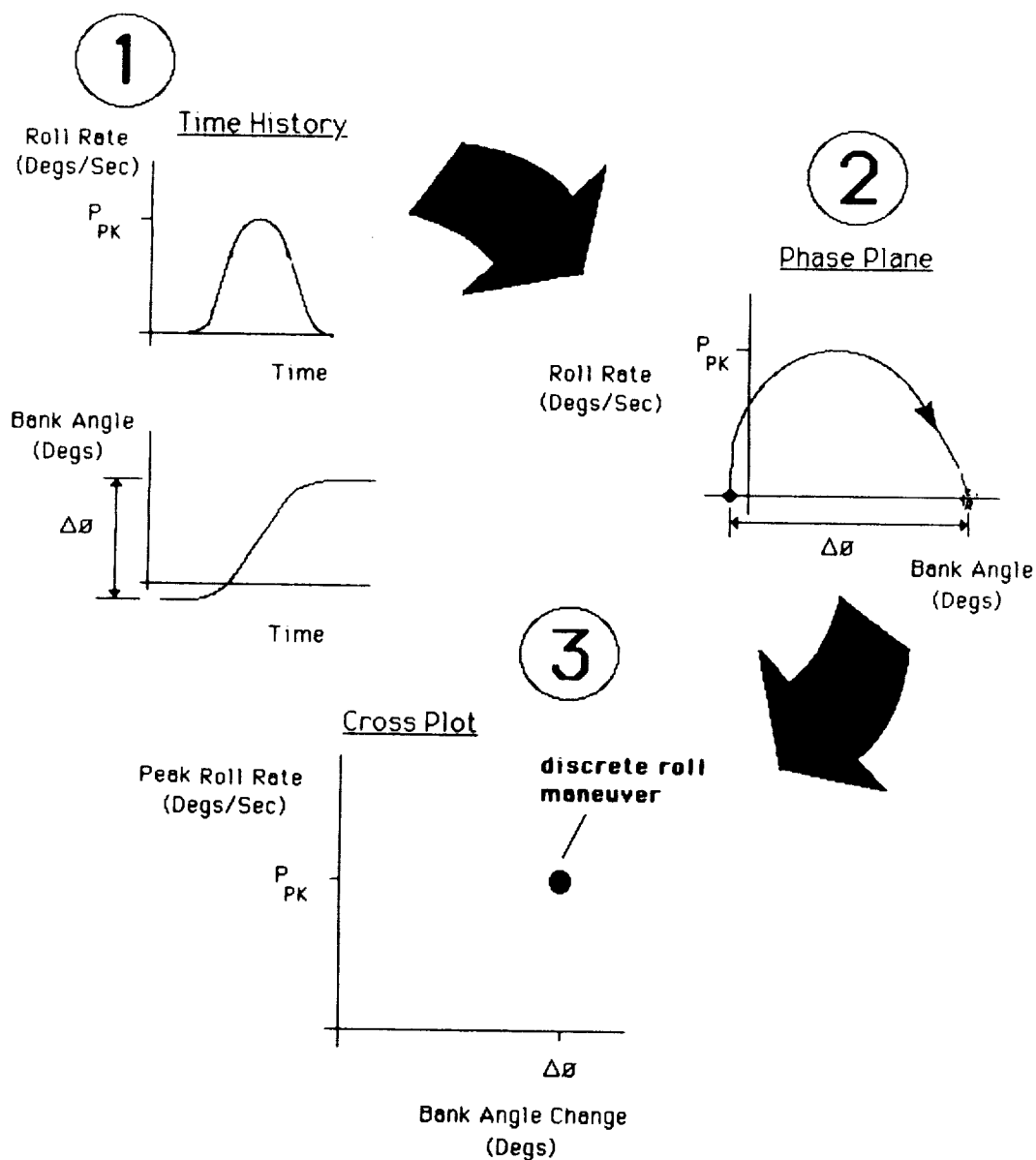


Figure 12. Analysis Technique for Discrete Roll Maneuver Data.

Another device used in the determination of handling qualities was a variable time loading procedure. In the course of experiments it was found that pilot ratings could be affected dramatically by the time available to the pilot. This also led to the idea of connecting handling qualities to the basic mission performance parameters of a design.

The general results from time-loading variation are described in Figure 13. For a given vehicle configuration (aerodynamics, flight controls, displays, etc.), the pilot ratings will not vary substantially until the pilot begins to suffer an insufficient amount of time to complete the task. At that point ratings can be expected to worsen sharply as the time available for the task is reduced further. This is referred to as the "critical" range of time loading. Where time is adequate is considered the "subcritical" range.

The time-loading factor is believed to be important because it represents an experimental variable heretofore neglected. Normally the pilot has been allowed to set the time loading based on his or her judgment of reasonable task execution. The fallacy is that task execution is likely to be varied by the pilot depending upon the vehicle characteristics. Faster execution would take place, for example, with a quicker-responding design.

The main difficulty with permitting task execution time to vary with vehicle response is that pilot rating distinctions can be diluted or attenuated. In effect, the rules for applying pilot ratings would be changing for each configuration.

The approach to this problem was to enforce strict task performance standards and, where necessary, to actually perform an intentional experimental variation in task performance in addition to the variation in vehicle configuration.

It should be noted that the time-loading variation need not always be in terms of time explicitly. Other task performance features can also be considered if they are suspected to be varying from one configuration to another. One example is the range-to-target in the ACM tracking task.

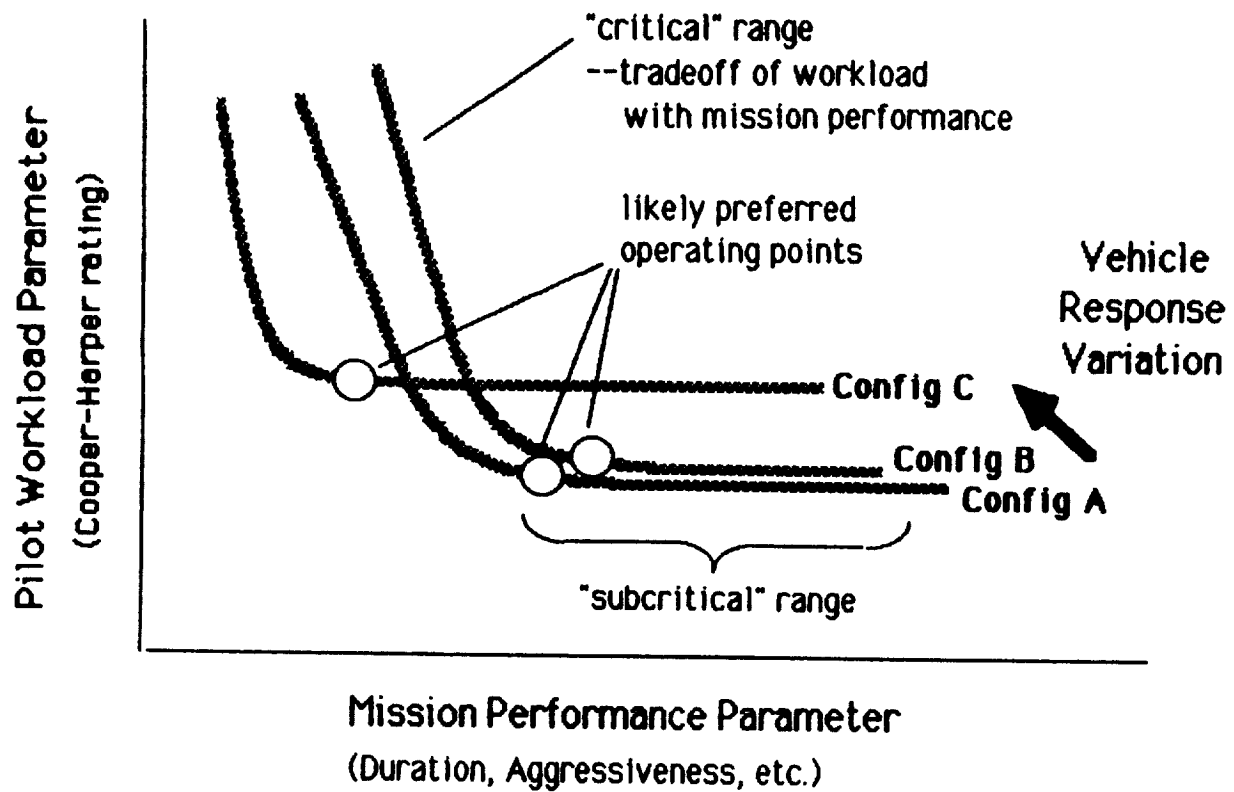


Figure 13. Generalized Effects of Task Performance and Vehicle Configuration on Pilot Rating.

IV. EXPERIMENTAL RESULTS

The experimental results involve both objective pilot performance as well as a subjective pilot opinion data. In general, steps were taken to quantify how the pilot performed maneuvers along with how they were rated.

Where possible, simulator results were compared with actual flight results in order to determine whether tasks were being performed in a valid manner.

In the following pages the results are presented and discussed generally according to the handling qualities features being studied, that is in terms of control power, short-term response, control sensitivity, etc. Results from other recent flight and simulator experiments in Europe and Canada are also discussed.

A. Control Power Experiments

Control power experiments were conducted first and were aimed at establishing the fundamental control power metrics and dependence on task. A representative generic vehicle was used (based on the UH-60 helicopter) and both conventional and augmented flight control response forms were investigated.

A broad range of tasks were explored ranging from very low-amplitude/low-aggressiveness instrument tasks to large, highly aggressive air combat maneuvering tasks. Within each task, attention was given to possible variations in degree of amplitude or piloting technique.

The specific tasks investigated during this phase were:

- HUD roll tracking task
- Lateral unmask/remask (sidestep)
- Air combat tracking

For each of the tasks, the nominal level of performance relative to control power was measured. This consisted of permitting the pilot to fly the tasks without encountering any control power limits.

The next step was to progressively reduce the amount of control power and measure the degradation in task performance and handling qualities using the Cooper-Harper rating scale.

1. Nominal Flight Task and Maneuver Performance

First the nominal maneuver performance was obtained by having the pilot fly several basic maneuvers without experiencing

control power limits. The first of these was the HUD tracking task. Typical results are shown in Figure 14.

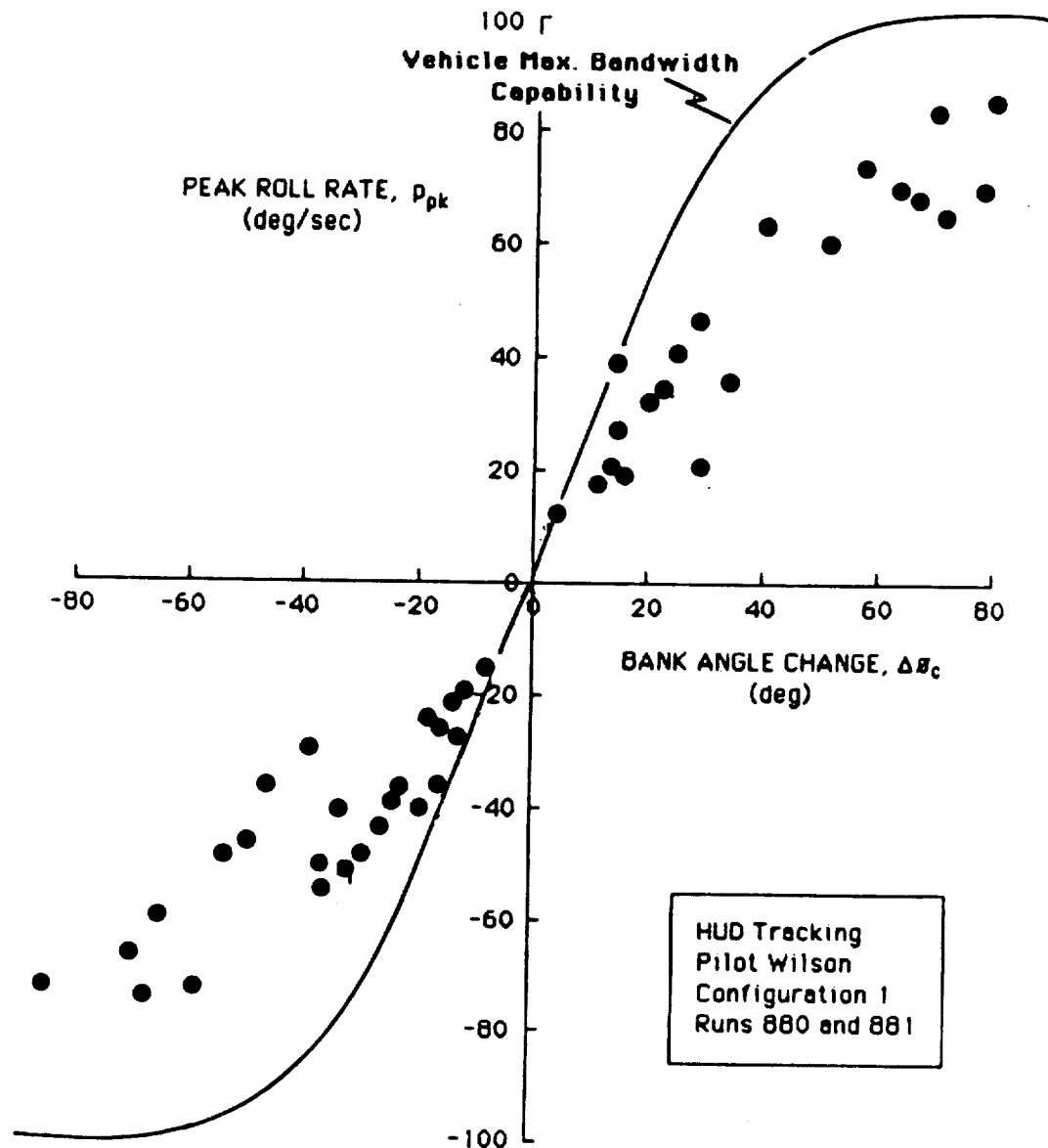


Figure 14. Typical HUD Tracking Performance Illustrating the Maximum Roll Rate Trend.

The lateral unmask/remask maneuver is fundamentally different from the HUD tracking task in that an "outer" control loop is also involved, i. e., lateral position. Thus the pilot uses the inner-loop control of bank angle to support the lateral position control task.

Figure 15 shows the typical maximum roll rate trend for the lateral sidestep task without control power limits being reached. Note that the amplitude of the maneuver is considerably less than that for the HUD tracking task in terms of both peak roll rates and bank angle changes.

The crosshatched corners indicate an engineering judgment of the maximum peak roll rate and maximum commanded bank angle change. Note that in the case shown in Figure 15, some data points exceed these judged maximums, but they are believed to be anomolous relative to the overall trend indicated by the remaining points. A more rigorous statistical standard should be defined eventually.

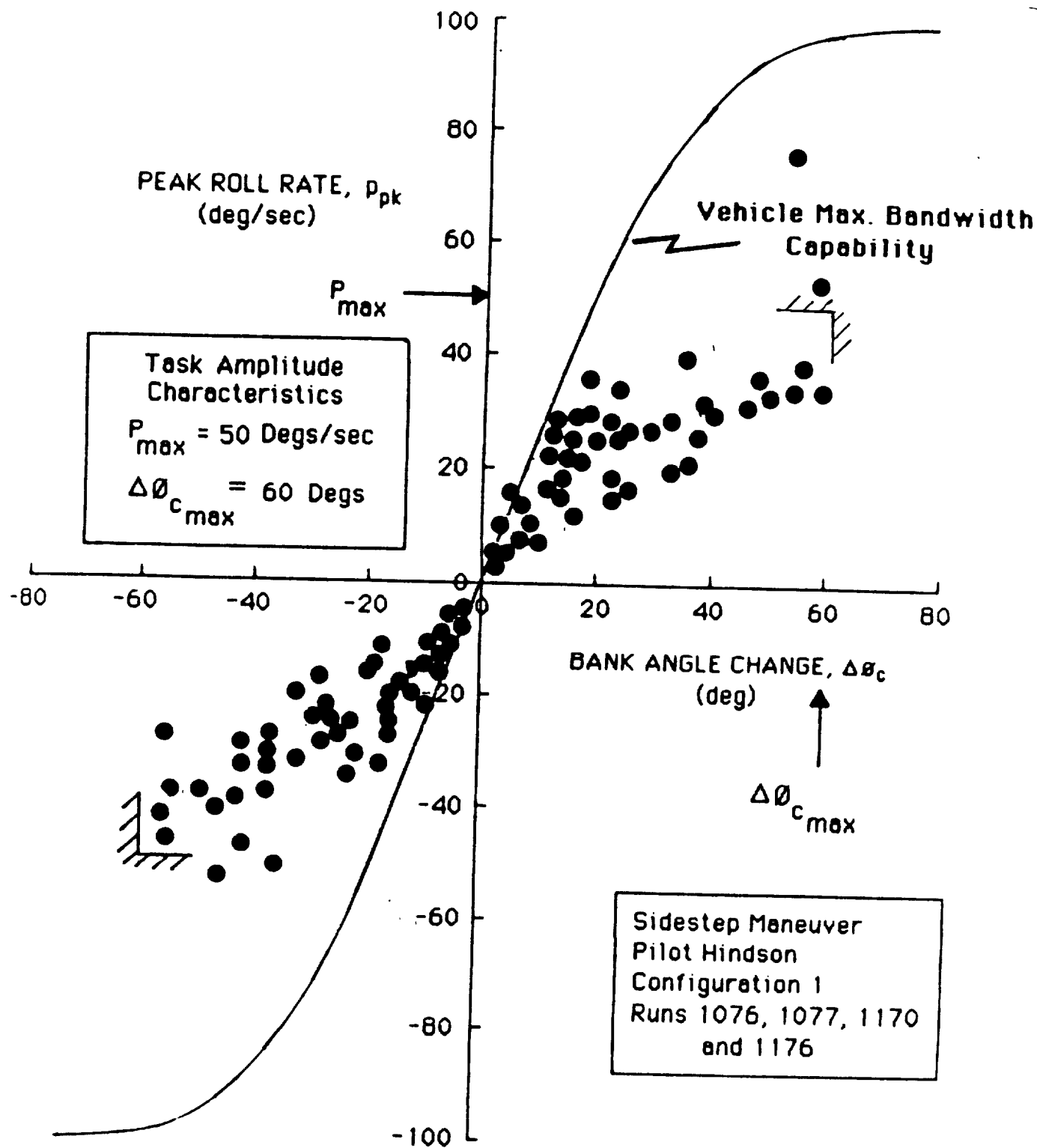


Figure 15. Typical Lateral Sidestep Performance Illustrating the Maximum Roll Rate Trend.

The air combat tracking maneuver is a third important flight task involving roll control power since it involves large-amplitude maneuvering for up-and-away forward flight.

Typical performance is illustrated in Figure 16. Amplitudes are generally higher than for the lateral sidestep task but still less than for the HUD tracking task.

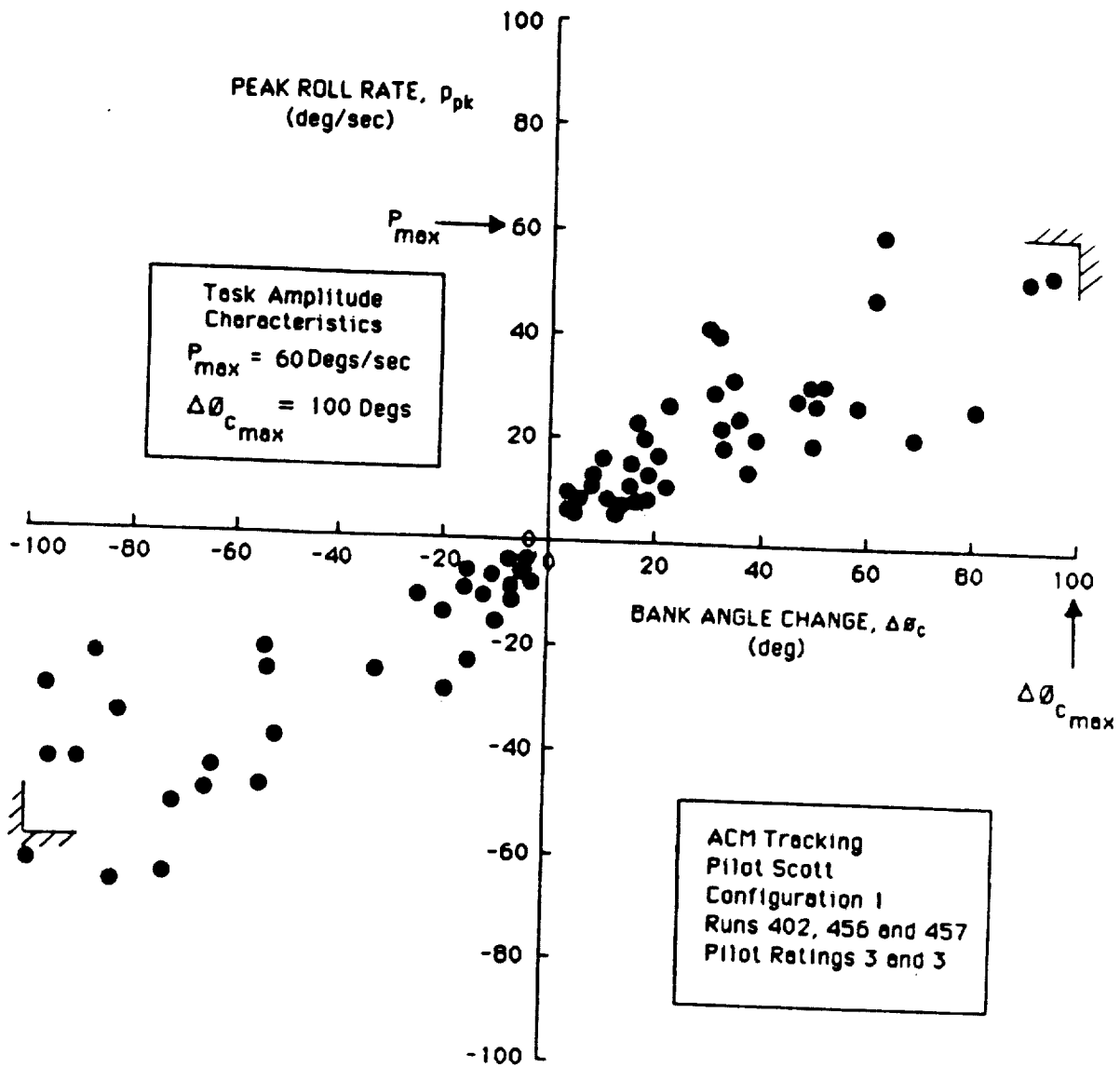


Figure 16. Typical ACM Tracking Maneuver Performance. Illustrating the Maximum Roll Rate Trend.

2. Effects of Control Power Reduction

The effect of control power reduction was studied by systematic reduction of roll rate capability. Results for the HUD tracking task are shown in Figure 17. Maximum roll rate available is systematically reduced through 100 , 67, 33, and 17 deg/sec.

The general pilot rating trends for reduction in control power available relative to control power required are shown in Figure 18. Note that as control power was reduced below 67 deg/sec the roll rate peaks were also reduced. At the same time, roll rates in excess of the theoretical capability could frequently be produced by uncoordinated turn activity by the pilot.

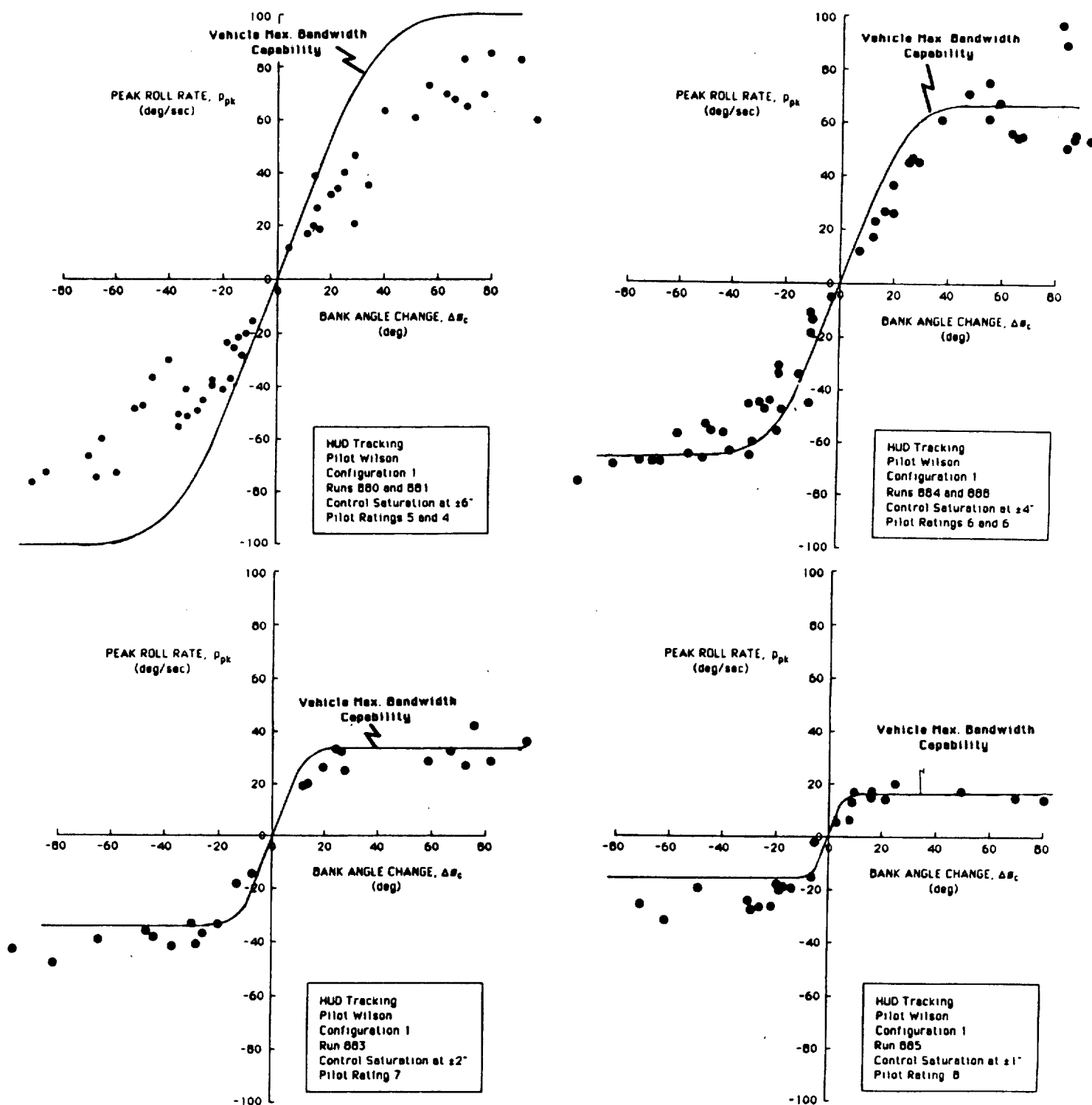


Figure 17. Nominal HUD Tracking Performance with Maximum Roll Rate Capability Progressively Reduced.

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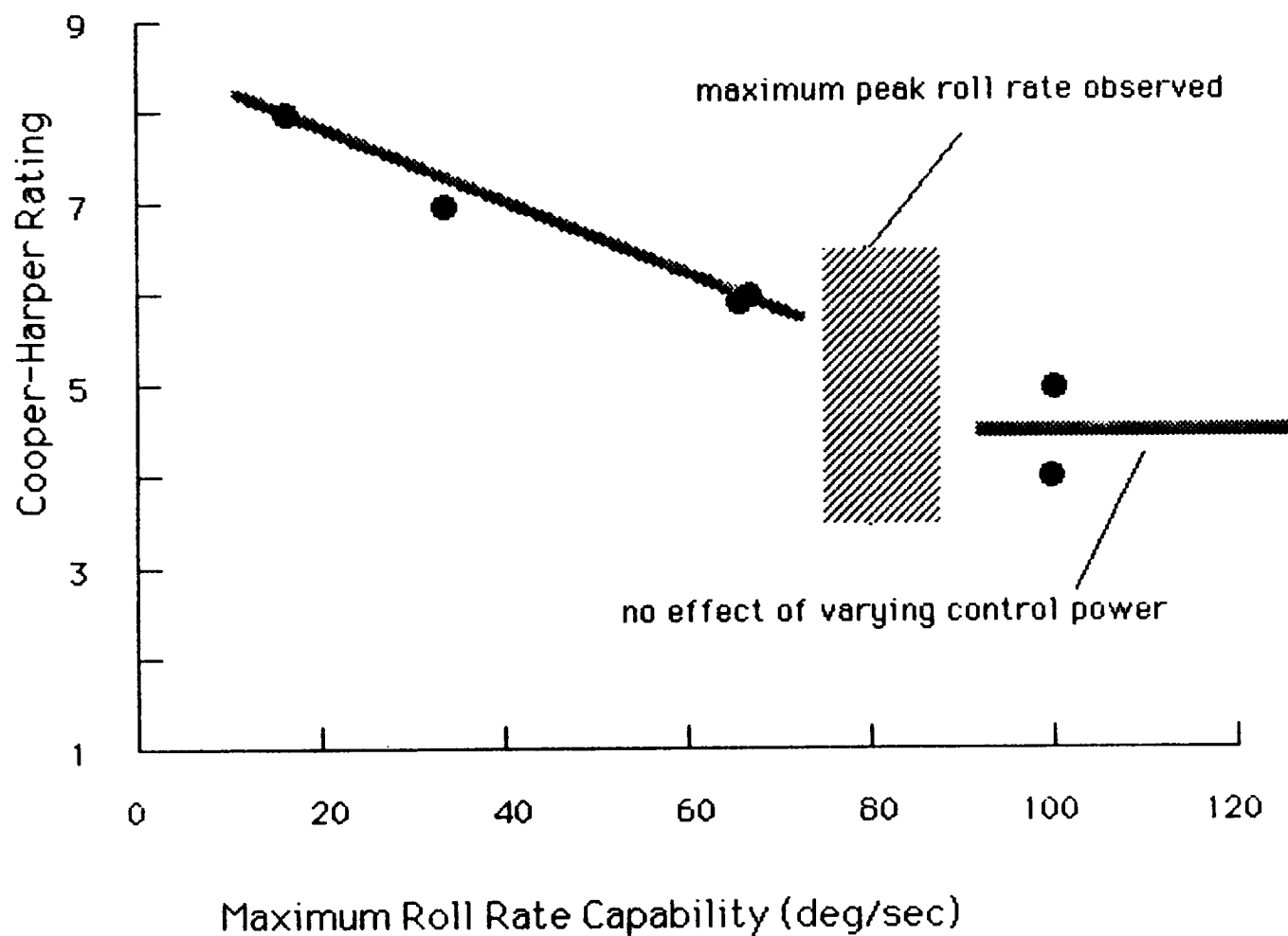


Figure 18. Variation of Pilot Opinion With Control Power Availability.

3. Comparison Between Simulator and Actual Flight

Where possible the performance of flight tasks and maneuvers were compared between simulation and actual flight. This was done by examining peak roll rates and bank angle changes as illustrated above.

The results from two crucial maneuvers, the lateral sidestep and air combat tracking, are shown below. Figure 19 compares flight and simulation for the sidestep. This was a direct comparison in terms of both the pilot and the vehicle (UH-1H). Note that simulation produced generally higher roll rate peaks although the proportion of p_{pk} to bank angle change was about the same. This kind of result would suggest that simulation might yield a somewhat conservative usage of control power. It is believed that this is a consequence of flight safety considerations rather than simulator fidelity. In this particular case the pilot expressed safety concerns for exceeding this level of performance in the actual helicopter.

Comparisons for the ACM task were made using flight data obtained from Army-sponsored evasive maneuver testing conducted at the U. S. Navy Test Pilot School. These data are described in Reference 22.

Figure 20 shows that the ACM data compare favorably between flight and simulator, but there are important factors to recognize. First, roll rate and roll attitude limits were in effect for flight tests and these had a generally inhibiting effect on pilots. Second, there was not a direct comparison of ACM maneuvers. The flight data reflect results of "scissors maneuver" roll rates, a decidedly aggressive event. Simulator data were taken from the tracking task described earlier.

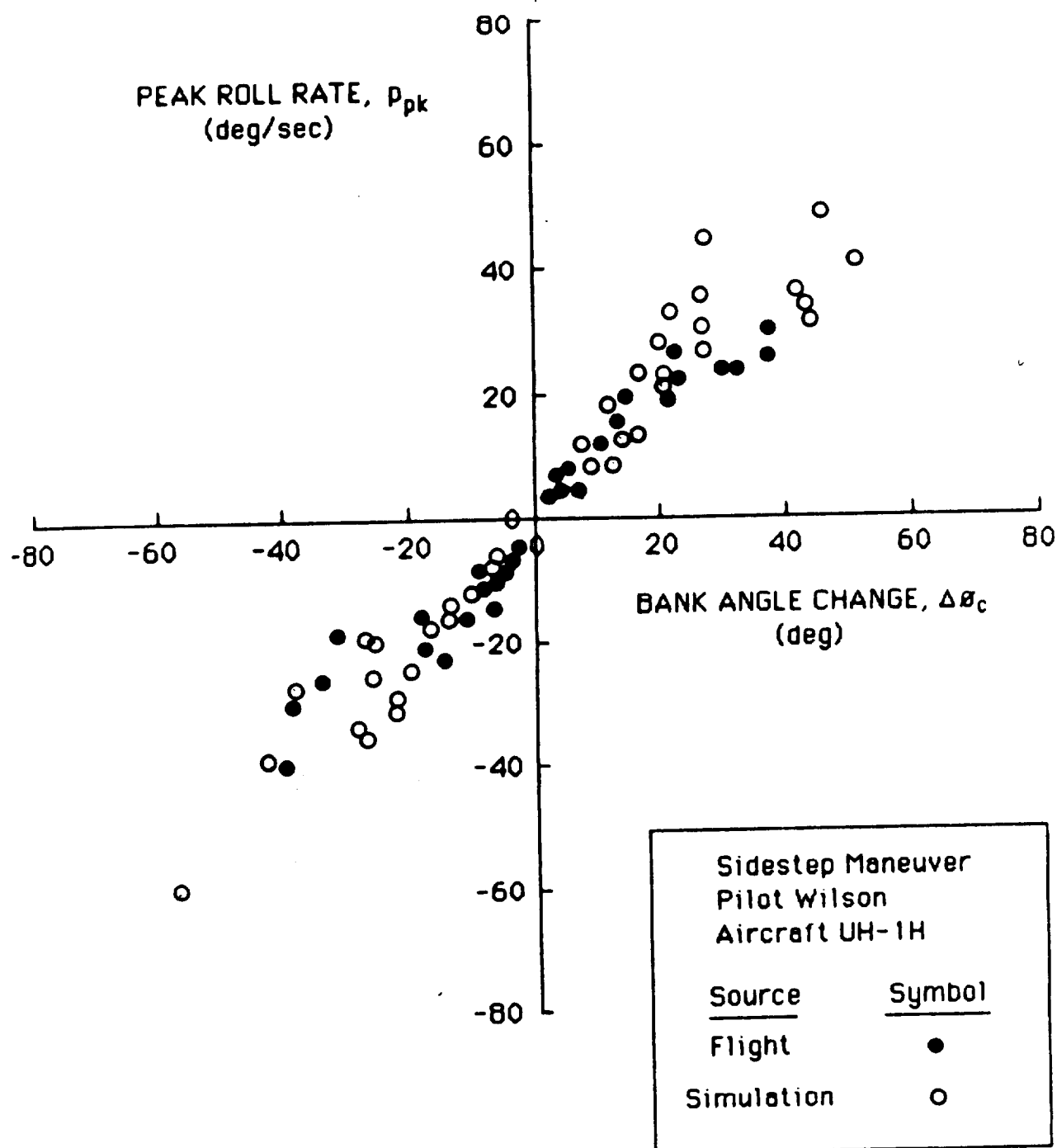


Figure 19. Comparison of Sidestep Performance Between Flight and Simulation.

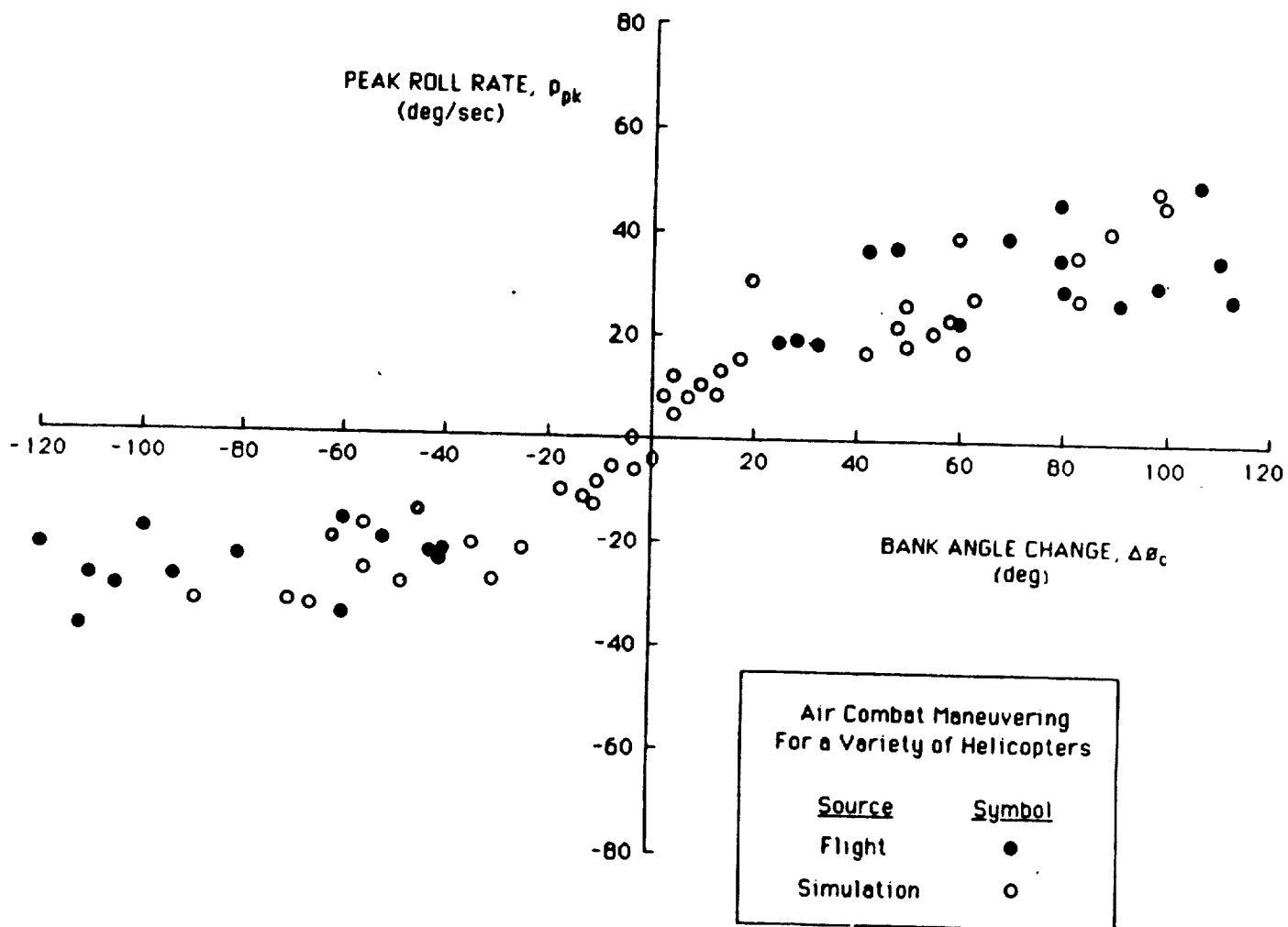


Figure 20. Comparison of Air Combat Maneuvering Performance Between Simulator and Flight.

Results of flight and simulator tests flown in the UK by the Royal Aeronautical Establishment are also useful in assessing control power requirements based on task performance. Reference 23 presents peak roll rate data for a number of maneuvers and aircraft. These data generally agree with the results obtained here.

One important aspect of the RAE data is the demonstration of how very large peak roll rates (hence control power) are required to follow tightly constrained ground tracks. This was demonstrated using "triple-bend" courses on a simulator. These data were later analyzed in Reference 24 and used to formulate a useful math model of roll performance as a pilot follows a curving path with respect to the ground. (A portion of this analysis is presented in Reference 3.)

The notable result is that flight experience to date has not produced very high peak roll rates (all less than 90 deg/sec) compared to the simulator triple-bend maneuvers. However, future maneuvers which may involve precise sharp turns or evasive maneuvers could result in higher roll rates, hence larger amounts of control power than found at this time. It is therefore useful to determine handling qualities criteria as functions of specific mission or task requirements as shall be demonstrated here.

The German DFVLR has also produced a substantial amount of flight data which defines peak roll rates and control power required. Slalom and figure-eight maneuvers were flown and results presented in Reference 25.

The DFVLR experiments involved use of an error performance metric in evaluating pilot skill and learning prior to obtaining ratings. This strongly influenced Manudyne's development and use of highly quantitative task performance standards and the time-loading assessment procedures.

4. Control Power Dependence upon Short-Term Response

The amount of roll control power required appears to have some degree of dependence upon the short-term response available, at least for realistic multi-loop flight tasks. This was investigated briefly by analyzing the amount of control power used (i. e., maneuver amplitude) during the second phase of VMS experiments.

The effect of vehicle control bandwidth (as reflected by flapping stiffness) on peak roll rate and bank angle change is shown in Figures 21 and 22, respectively. These plots indicate a distinction between Level 1 and Level 2 handling qualities which was found by cross plotting results. In general, the combination of good performance and quick response (a combination which corresponds to Level 1 handling qualities) decreased the peak roll rates utilized below an inverse bandwidth of about 0.5 sec. At the same time, regardless of HQ Level, slower response characteristics generally correlated with (and probably induced) smaller peak roll rates. Maximum required control power can be expected for Level 2 handling qualities but involving a quick short-term response.

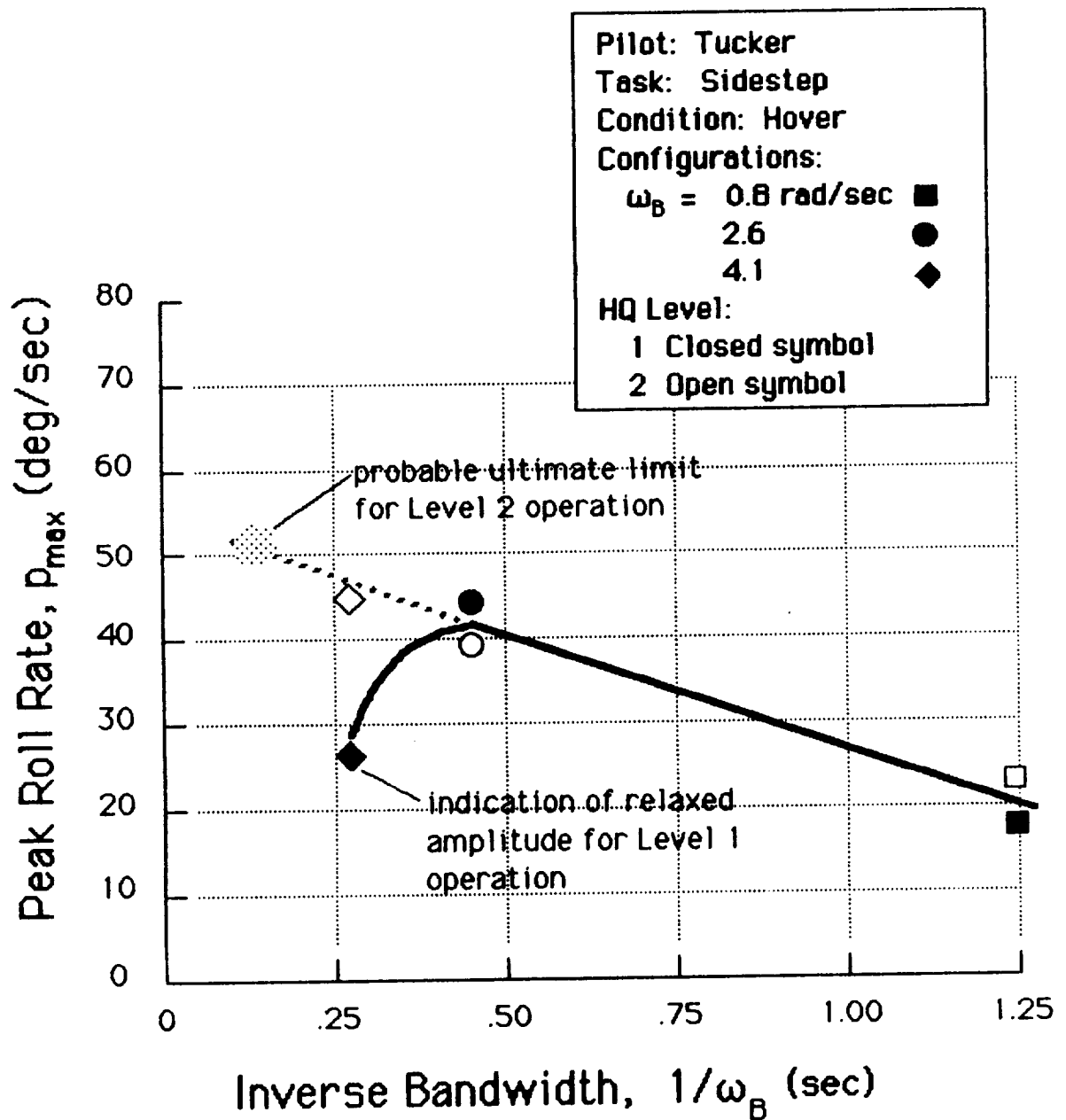


Figure 21. Effect of Flapping Stiffness on Maneuver Amplitude (Peak Roll Rate).

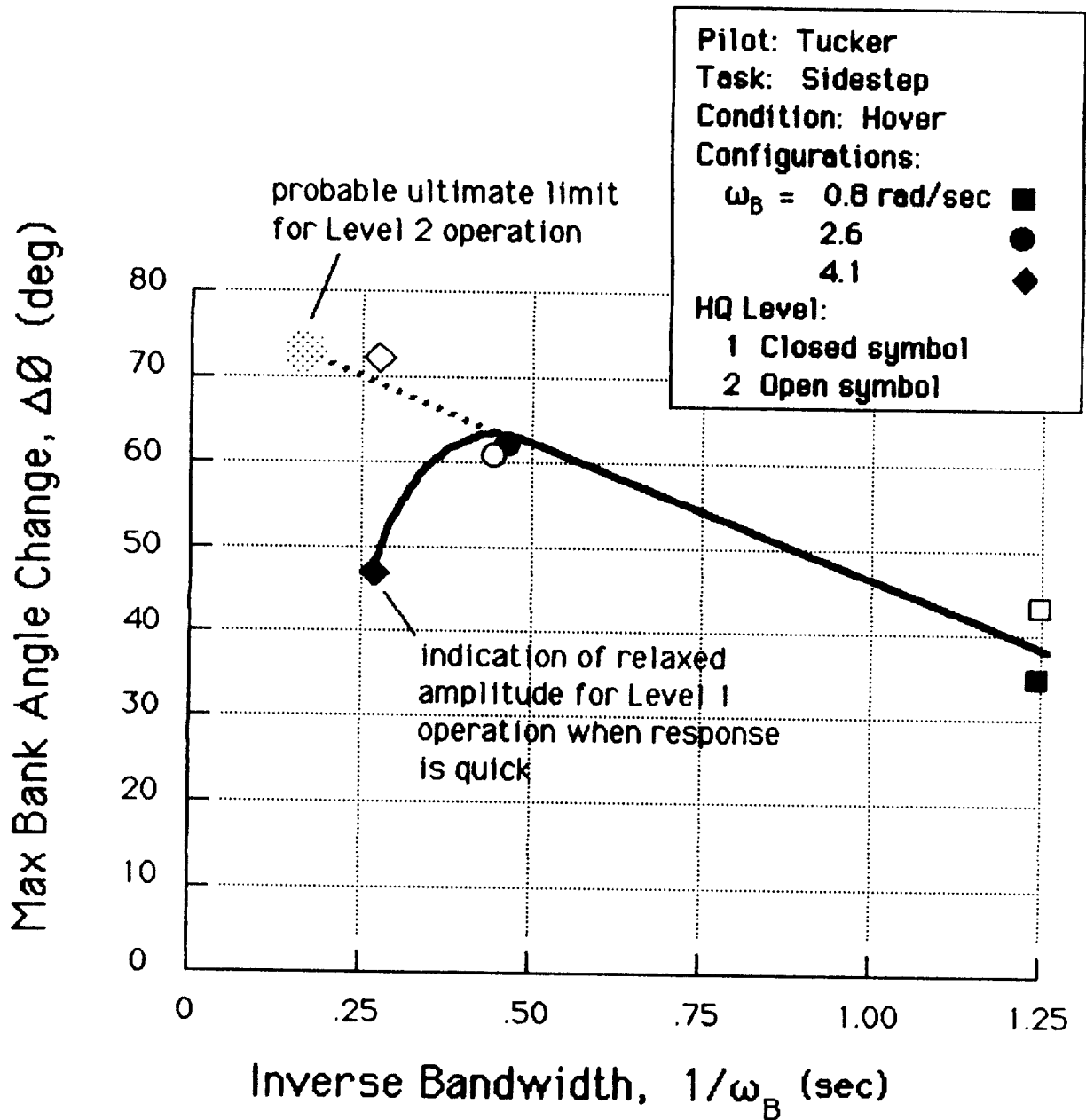


Figure 22. Effect of Flapping Stiffness on Maneuver Amplitude (Max Roll Excursion).

B. Short-Term Response Experiments

Short-term response results were obtained for several important tasks.

The quality of short-term response results was highly dependent upon the increased computer speed and reduced throughput delay available for the second phase of simulation.

In general, the intentional time-loading techniques were found important in exposing short-term response effects.

1. Flight Task and Maneuver Performance

The three main flight tasks studied in the short-term response phase (HUD tracking, lateral sidestep, and ACM tracking) provided a range of performance generally useful for relating pilot aggressiveness to vehicle quickness.

The HUD tracking task, a well-controlled but somewhat artificial task, was used to gain an upper bound on the effect of short-term response on pilot rating.

The lateral sidestep was considered to be a realistic task but required maximal use of simulator fidelity in order to perform the task in a normal closed-loop fashion. The elimination of visual system delay, reduction of computer frame time, and use of good quality cockpit controllers were all essential to success of this maneuver.

The ACM tracking task was likewise performed successfully but was dependent upon the manageability of the target aircraft's actions, elimination of system delays, and maintenance of coordinated turns for the ARMCOP math model. Consistency of ACM performance was generally found so long as the strong effect of range-to-target was recognized by the experimenter.

2. Effects of Short-Term Response Variation

The result of varying short-term response (flapping stiffness) for the HUD tracking task is shown in Figure 23. Note the strong, essentially linear variation of Cooper-Harper rating with the inverse square root of L_{b_1} . The consistency of

these results is believed to rest on the tight task definition, care exercised in maintaining near-optimum control sensitivity in the vehicle (found by independently varying), and adequate control power. Thus only one handling qualities feature was actually varied in the experiment.

The value of the above data is in establishing an upper limit on the range of useful flapping stiffness for a simple task. This shows, for example, that bandwidths above about 6 rad/sec are not effective in further improvement in pilot rating.

However the limitation of the HUD tracking task is that it is rather artificial and does not correspond well to an operationally useful task or maneuver. For this the lateral sidestep and ACM tracking tasks were examined.

A set of preliminary results for varying flapping stiffness with the lateral sidestep task are shown in Figure 24. Note the much reduced effect of flapping stiffness on pilot rating compared to the HUD tracking task in addition to the increased variability. Such results were taken as an indication that there were unaccounted sources of variability. Since the vehicle characteristics were not being changed and the same pilot was involved, variations in the task were suspected.

Lateral sidestep data are shown in Figure 25, but also with regard for how quickly the task is performed. It can be seen that without considering task duration, pilot ratings can be scattered and not particularly repeatable.

For both the lateral sidestep and ACM tracking tasks it was found that the impact of short-term response, by itself, could not be adequately evaluated without carefully tracking pilot performance. The reason for this is that the pilot can unknowingly change task performance standards as the vehicle response is varied. A very quick short-term response could be expected to induce faster performance of a sidestep, for example. In order to account for such an effect, it was decided to examine "time-loading."

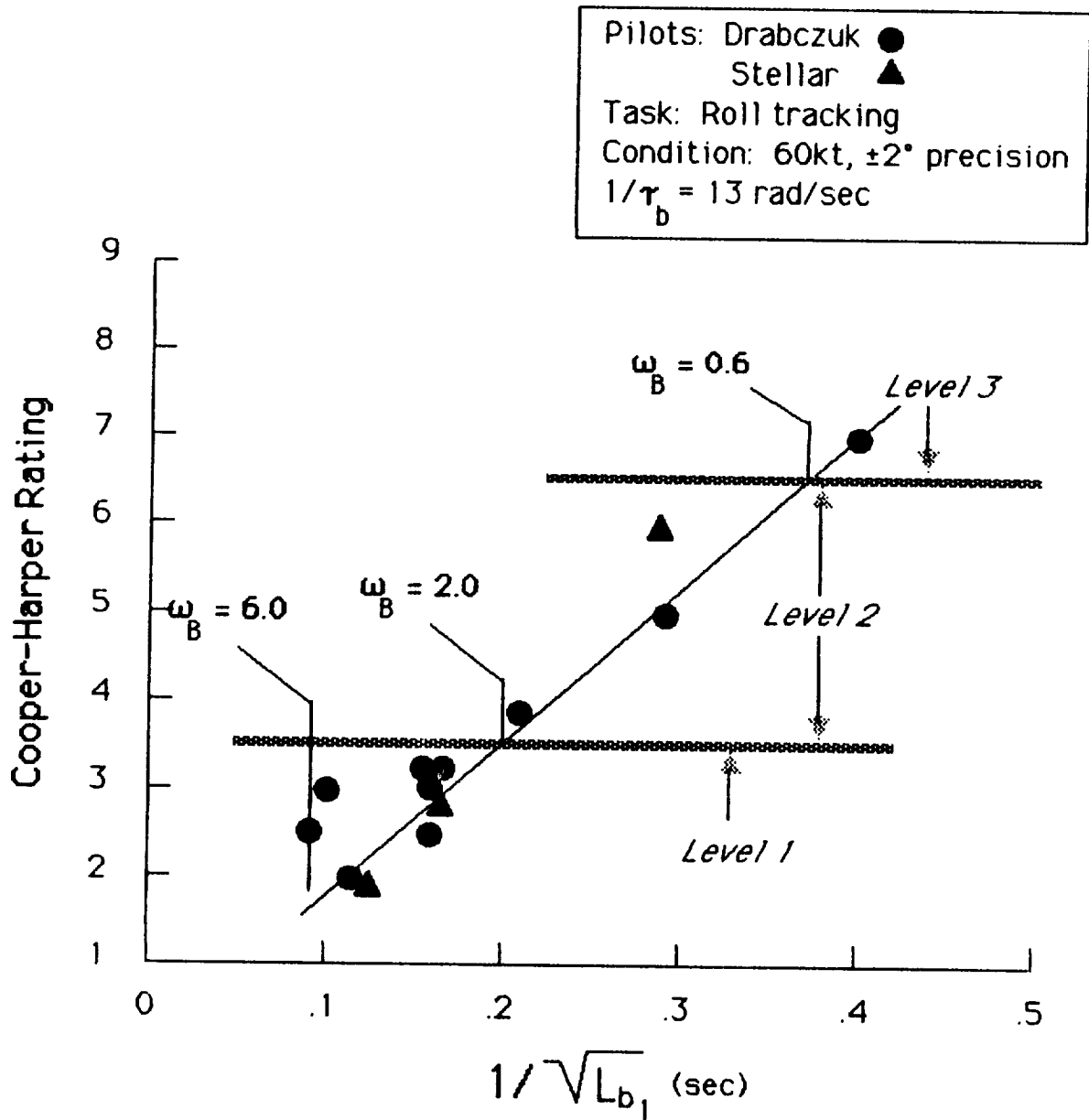


Figure 23. Effect of Flapping Stiffness for the HUD Tracking Task.

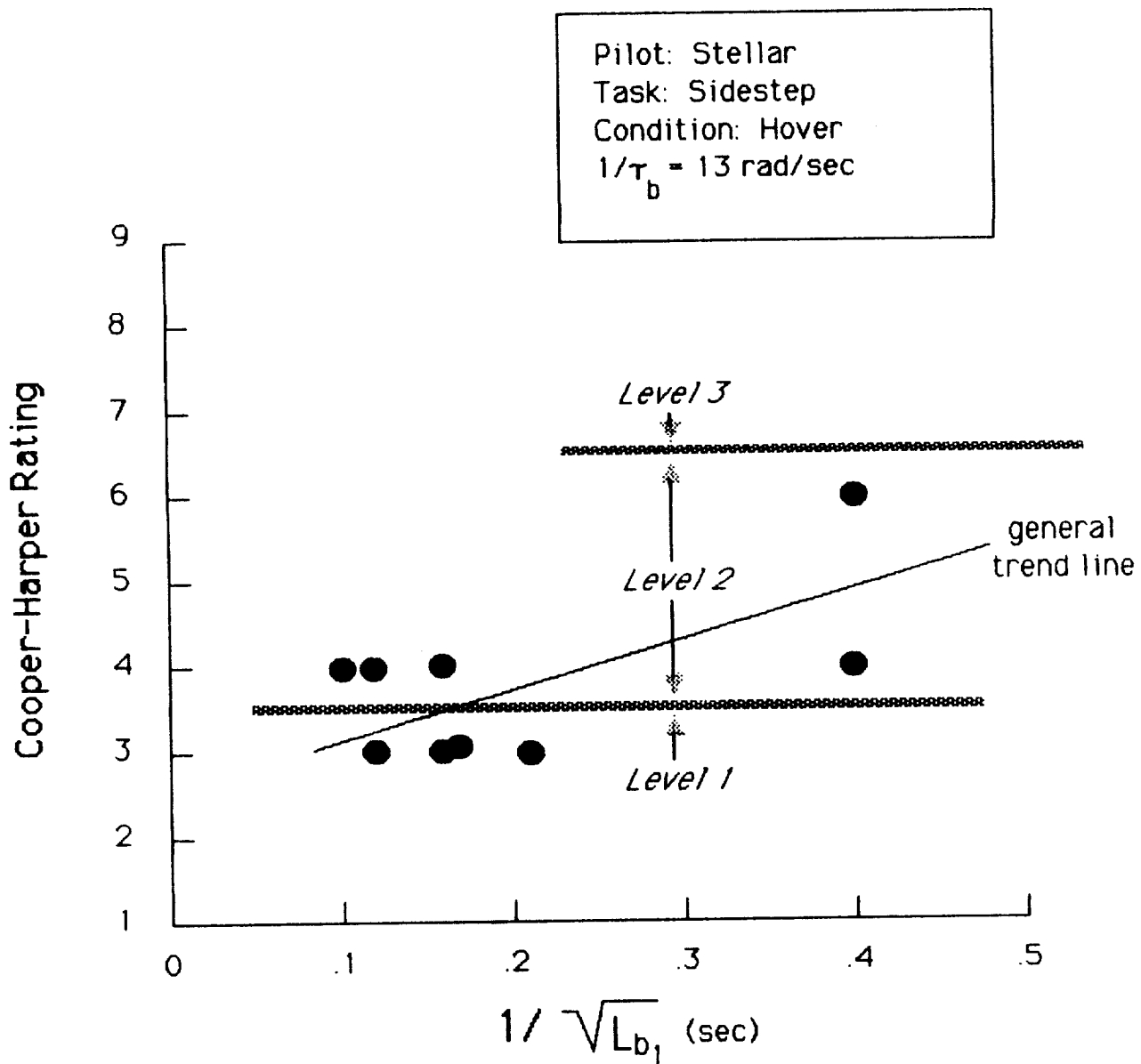


Figure 24. Effect of Flapping Stiffness for the Lateral Sidestep Maneuver Without Regard to Task Duration.

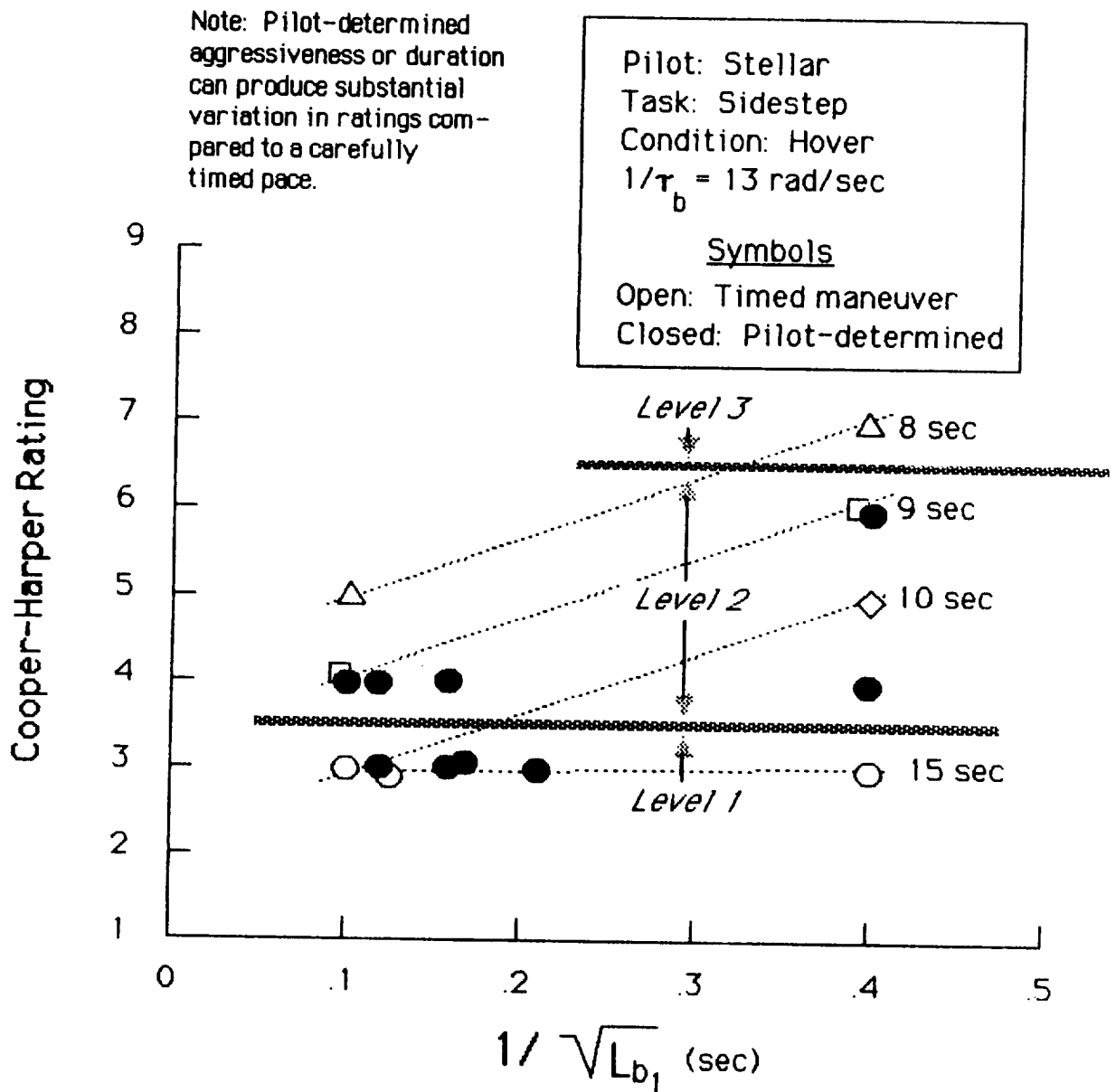


Figure 25. Effect of Flapping Stiffness for a Lateral Sidestep Task Including Regard for Task Duration.

3. Dependence upon Time Loading

A given amount of short-term response can be found satisfactory for one level of task performance, but unsatisfactory for another. Therefore it is imperative that short-term response be evaluated relative to a given task performance standard. This was done for both the lateral sidestep and ACM tracking tasks by recognizing the major task performance features in each case.

In effect two experimental variables were considered at once: (i) vehicle short-term response and (ii) a crucial task performance parameter. The independent task variable for the lateral sidestep was the task duration and for ACM tracking it was the average distance to the target. Thus a cross plot of results could be used to indicate the effect of vehicle response without unintentional covariation of task performance.

Another important result of this procedure was to establish clear linkage between handling qualities features and their role in achieving crucial mission performance requirements. In this way the real purpose of handling qualities was made more clear, that is, to support mission performance objectives.

For the lateral sidestep, short-term response was shown to be strongly conditional upon task duration, i. e., the time to perform a complete, stabilized sidestep to a new position. This is illustrated in Figure 26. Note that for each value of flapping stiffness the lateral sidestep can be performed more or less quickly without suffering a pilot opinion degradation. Further, below a certain duration time, pilot rating worsens sharply.

These results suggest that specification of short-term response implies a task performance capability. If that task performance is not compatible with the design mission (e. g., to avoid radar lock-on while performing a lateral unmask/remask) then the handling qualities requirements are insufficient.

This can be better viewed in Figure 27 which is a cross-plot of these same data. Note that the choice of minimum bandwidth for Level 1 or Level 2 varies widely for the task duration needed.

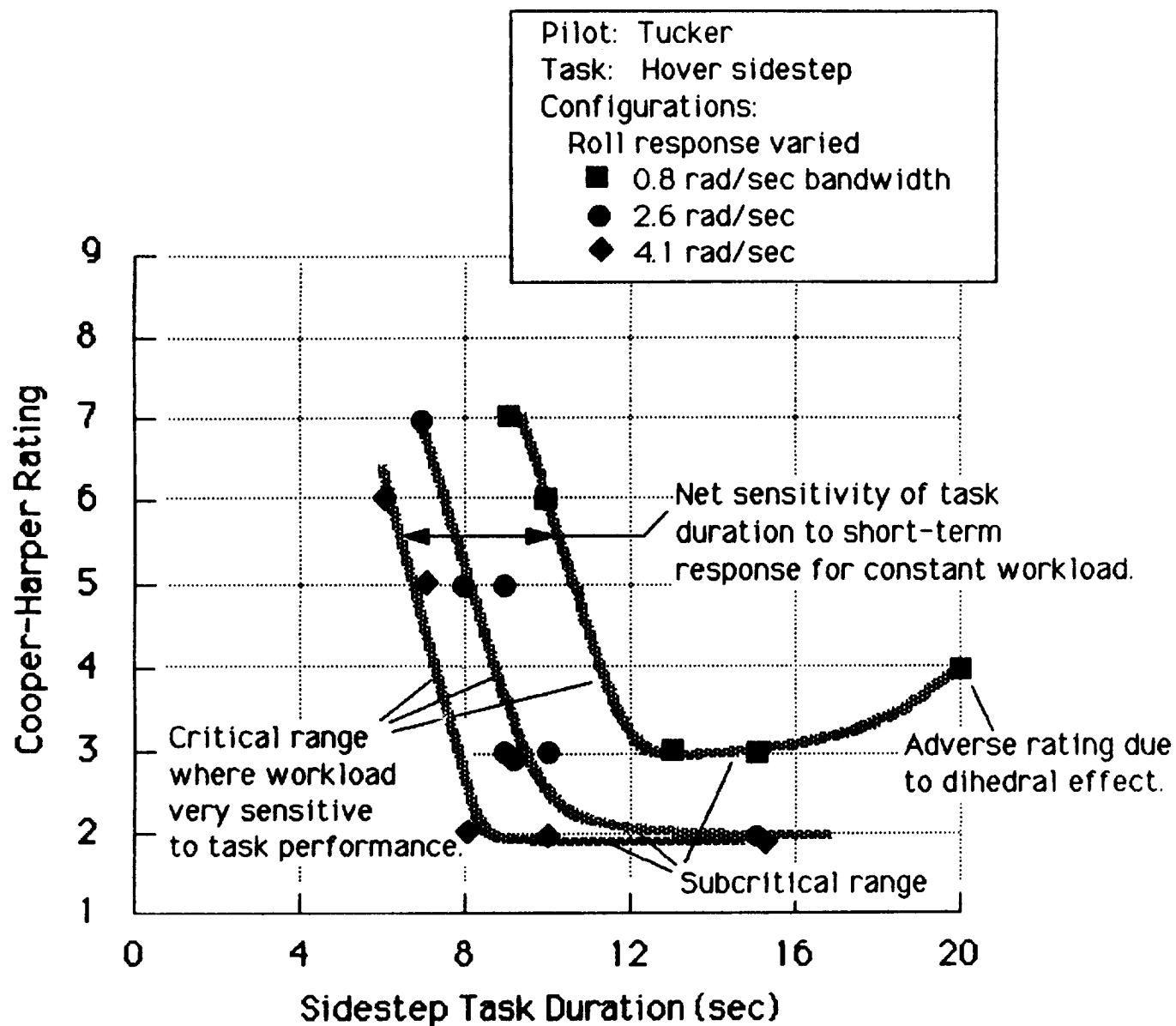


Figure 26. Effect of Short-Term Response as a Function of Sidestep Task Duration.

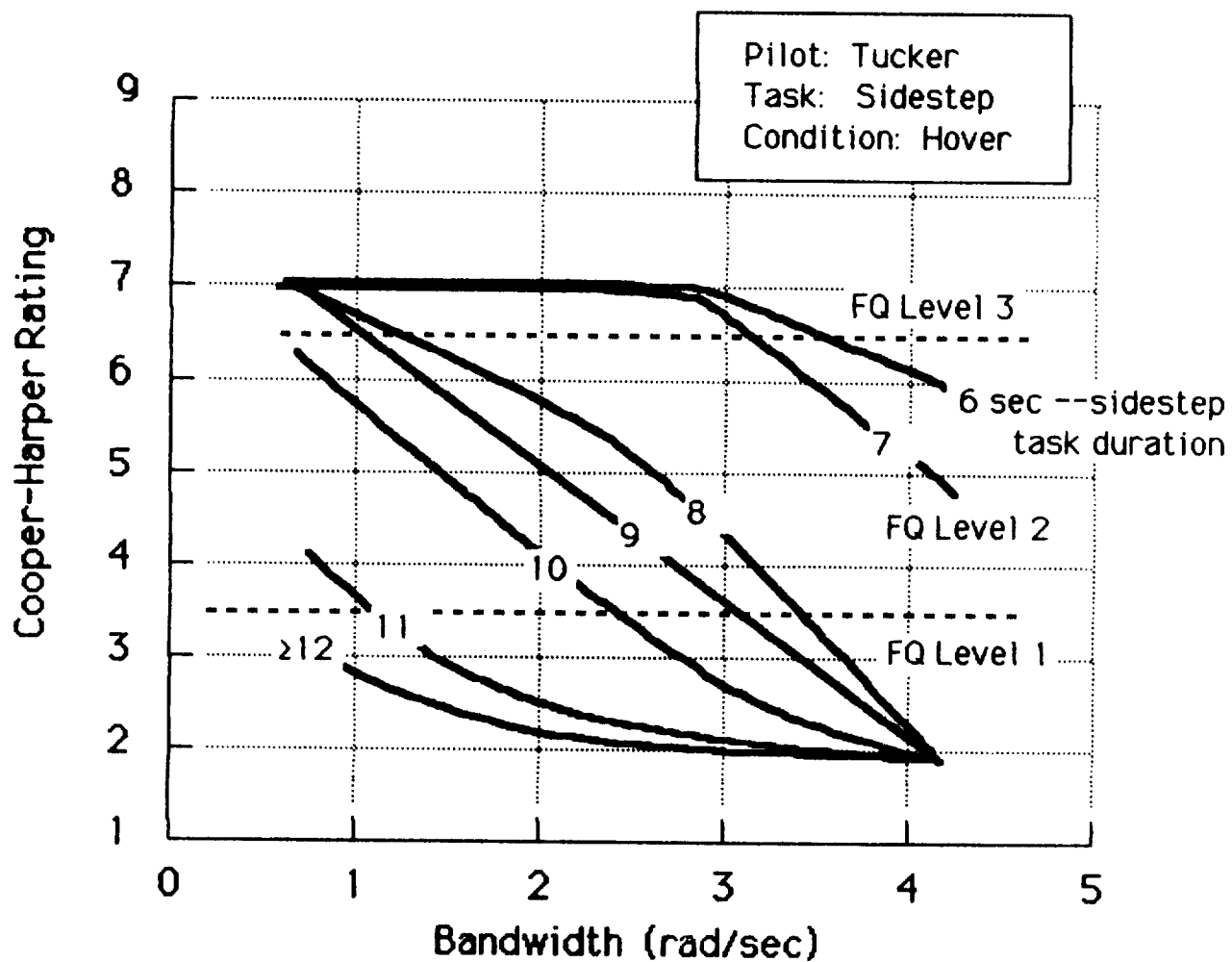


Figure 27. Effect of Vehicle Response on Pilot Rating as a Crossplotted Function of Task Performance.

The ACM tracking task was examined in a similar manner. The task was varied but with respect to the average range to the target rather than an explicit time parameter.

Figure 28 shows how target range affects pilot rating for varying short-term response features, including flapping stiffness and control response type.

Additional confirmation of the ACM results was found in Bell Helicopter data acquired about the same time as the Manudyne results. Both the Bell and Manudyne data are plotted in Figure 29.

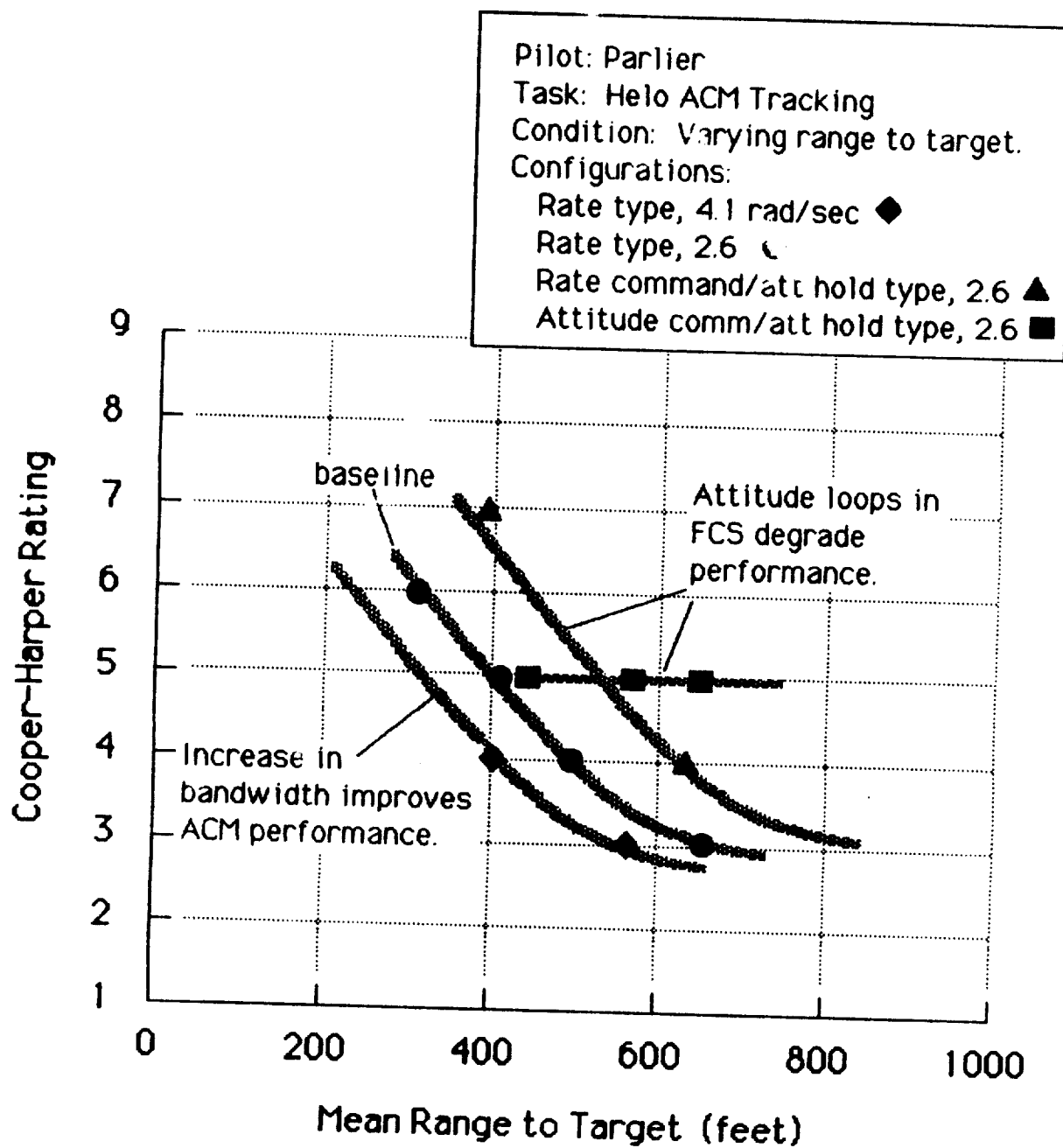


Figure 28. Effect of Short-Term Response as a Function of ACM Range-to-Target.

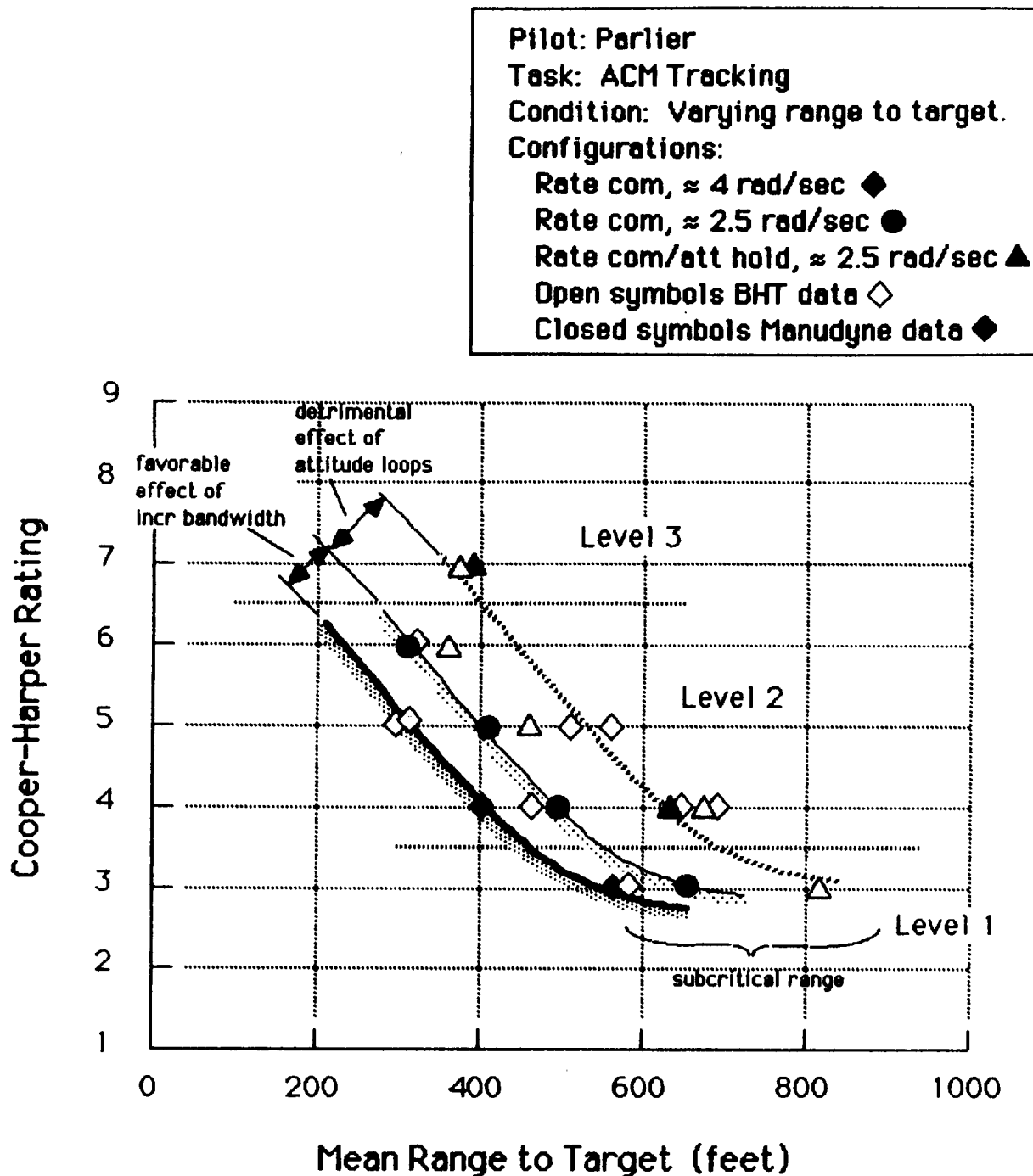


Figure 29. Additional Data for Short-Term Response as a Function of ACM Range-to-Target.

4. Effects of Transport Delay

The transport delay aspect of short-term response was examined briefly by turning off the 100 msec digital delay compensator. The effect was found to be considerable when a critical task duration was strictly observed.

Both the HUD tracking task and sidestep maneuver were used for examining the effect of delay. Although the delay compensator was the device used to introduce delay, it represented an effective delay in the pilot-vehicle control loop path and hence the equivalent of a control delay.

For the HUD tracking task, the critical condition for examining the delay was for a basic rotor response having an effective bandwidth of 6 rad/sec. With compensation on the effective delay was negligible and a pilot rating of 2 was obtained. Without compensation, a net delay of 100 msec was added and the pilot rating degraded to 5.

In the lateral sidestep task similar vehicle conditions were examined. The critical task/vehicle combination was chosen to be at a vehicle bandwidth of 4.1 rad/sec and a task duration of 8 sec. Figure 30 shows that in this case the pilot rating degraded from 2 to 6 with the introduction of 100 msec delay. A rating of 6 was also obtained without the delay but for a task duration of 6 sec. Thus the 100 msec of delay was directly responsible for either a rating degradation from 2 to 6, or for a task duration degradation from 6 sec to 8 sec for the same rating.

NOTE

A delay compensator can profoundly enhance workload or performance, but that tradeoff must be carefully tracked in order to measure the effect.

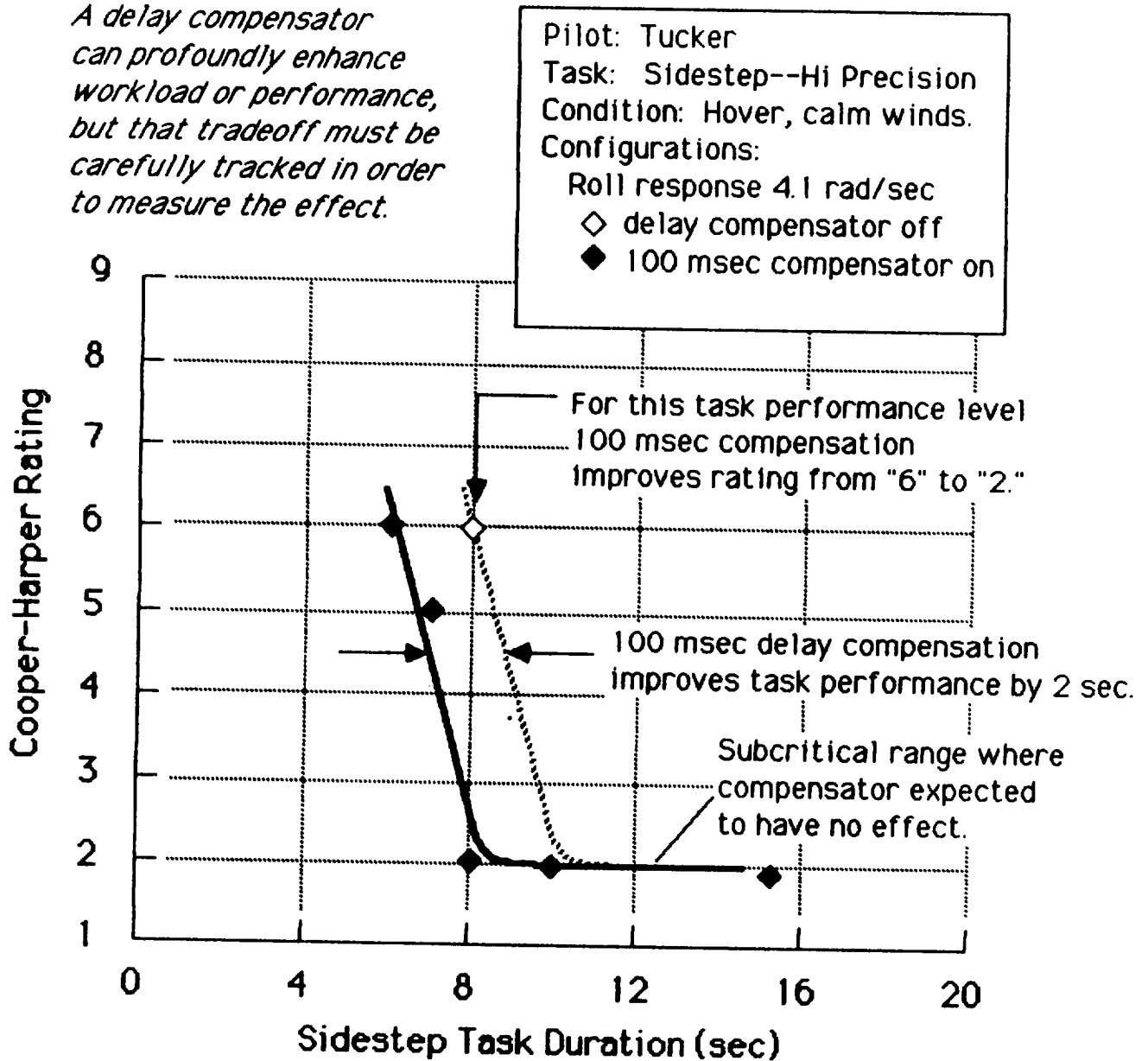


Figure 30. The Effect of Digital Delay on Critical Sidestep Maneuver Performance.

5. Other Flight and Simulator Data.

The recent RAE and DFVLR experiments mentioned previously also addressed short-term response characteristics.

DFVLR data were obtained for a slalom maneuver and presented in the traditional roll damping versus control sensitivity form (see Figure 1). Results for the task performed agree well with much earlier Reference 20 requirements suggested by Edenborough and Wernicke. It is significant that the DFVLR data were produced by an aircraft capable of very quick response (the BO-105's L_p is approximately -7.6). However there was not direct means of relating these data in terms of the task time loading conducted by Manudyne.

Some unpublished DFVLR data supplied to Manudyne were analyzed in terms of time loading. Specifically, BO-105 lateral sidestep durations were measured at 10 to 11 sec which should have been well within the "sub-critical" time-loading range but were rated at Cooper-Harper 5 and 6. Ratings of 2 were found in the simulator for comparable short-term response. However the difference could be attributed to the very substantial amounts of cross coupling found the BO-105 which make aggressive but precise lateral maneuvers difficult.

RAE short-term response data were evaluated in terms of the ratio of peak roll rate to net bank angle change for discrete maneuvers. Also a continuous maneuvering task was performed using several segments of constant-radius turns. For this a continuous track error was examined in order to obtain frequency-domain results.

One notable feature of the RAE test procedure was use of the "task agility factor," a measure of discrete-maneuver efficiency. This has similarities to the time-loading procedure used in this study. The task efficiency factor relates actual turn radius to a theoretical one based on speed and bank angle. The quickness or aggressiveness of turn entry and turn exit are thus the main task features addressed.

C. Control Sensitivity

Control sensitivity results were a byproduct of the control power and short-term response experiments. While control sensitivity is often viewed as a simple, easy-to-manage aspect of aircraft handling qualities, it nevertheless has a powerful effect on pilot opinion.

Control sensitivity was optimized as required in order to separate out the effects of short-term response. It was found that even experienced pilots could not distinguish well between control sensitivity and short-term response (bandwidth). This is because the two have an inseparable relationship which depends upon the dynamics of task execution.

In general, the results of control sensitivity experiments performed on simulators must be interpreted with care. It is well known that fixed-base simulators will produce optimum sensitivities higher than flight results. To an extent the large motion capability of even the VMS system should be used with caution in obtaining control sensitivity data.

It was hypothesized that control sensitivity evaluated near the region of crossover should be a reasonably consistent metric. For these experiments a crossover frequency of 2 rad/sec was assumed for this purpose. It was found that a roll rate to lateral stick proportion of about 15 deg/sec/in at this frequency did, in fact, generally correspond to the sensitivity considered "optimum" by the evaluation pilots.

D. Control Response Type

Most of the results obtained in this study were for a normal helicopter response shape rather than those of highly augmented vehicles. Two main difficulties prevented a more thorough study of such response types. First computational speed and delays, especially in the first simulation period, precluded adequate solutions to high-gain augmented systems. Second, the aerodynamic cross-coupling inherent in the ARMCOP math model became intolerable when high-gain augmentation loops were closed.

Nevertheless, some useful results were obtained for highly augmented systems. Both "rate-command/attitude-hold" and "attitude-command/attitude-hold" control configurations were examined.

About the same level of peak roll rates were produced with rate-command/attitude-hold systems as with conventional aircraft responses. This is demonstrated in Reference 3 for the sidestep maneuver. However, for attitude-command/attitude-hold systems the peak roll rate is strongly tied to the net bank angle change and cannot be used as a basic control power metric.

Both augmented response types were evaluated for the ACM tracking task, and those results were shown earlier in Figure 28. For an equivalent bandwidth, the rate command system with attitude hold was found inferior to the basic helicopter response in the critical range and about the same in the subcritical range. The attitude-command system was found substantially worse in the subcritical range but may have offered some advantage at very close ranges. This should be explored further in order to possibly minimize the usable target tracking range.

V. CRITERIA DEVELOPMENT AND ANALYSIS

The purpose of this section is to consider the results obtained in this study and propose handling qualities criteria which can be of use to the designer as well a procuring agency. In doing so, certain philosophical aspects will be discussed in addition to explicit treatment of the various handling features themselves.

Also, as a prelude to reading this section, it may be instructive to review a few selected sources dealing with helicopter handling qualities criteria in fairly general terms but with a view toward the current objectives of this study. Such sources should include References 26, 27, 28, and 29. The first two represent the status of helicopter handling qualities criteria just prior to the start of this program. The third represents the most recent overview and includes some of the results of this study. The fourth represents a manufacturer's view with particular emphasis on the air combat maneuvering aspects of helicopter operations.

A. Philosophy for Setting Criteria

Handling qualities criteria have been expressed in a variety of forms. The rationale and utility of these various forms are often neglected, and it seems reasonable to reflect on them at this point.

1. Connection to Task

One crucial and widely recognized factor in establishing handling criteria is the dependence upon the task. Unfortunately this is not generally reflected in existing criteria, except in a very loose and subjective way. While we see criteria set for "mild maneuvering" or "aggressive maneuvering," those adjectives are not well quantified.

2. Observability

There are several points from which to observe vehicle response and handling characteristics. These points of view can include the pilot, the engineer, the system designer, and the mission-effectiveness analyst. Depending upon which is picked, criteria can differ greatly in form and utility.

A "pilot-centered" point of view might include those very visible features such as overshoot, rise time, or control limiting. As a rule such features can be also seen in time history traces.

The "engineer-centered" point of view can be far more esoteric and abstract. Rather than overt time-domain features, the engineer might choose to work in terms of stability derivatives or frequency-domain features. Engineer-centered criteria

can also take the form of products , ratios, or complex functions of several varied parameters.

A special point of view can be that of the aircraft or system designer whose preference for basic design parameters such as "disk-loading," "thrust coefficient," or "hinge offset." These may have powerful influence over the handling features observed by the pilot, but not necessarily a unique cause and effect relationship.

One other point of view which could be considered in formulating handling criteria is that of the mission planner or mission-effectiveness analyst. This is not often considered, but some aspects of handling could be stated in terms of ability to achieve a level of mission performance or ability to evade a threat.

Thus one has many ways to express how criteria are observed and quantified. It may not be sufficient to restrict criteria to any one point of view.

3. Design Utility

The design utility is a special consideration here. Usefulness in the design process implies that a criterion is predictive of a given level of goodness.

4. Ability to Test

The ability to determine whether an actual vehicle meets a given criterion is a factor in choosing criteria, but might be of only academic interest once the design stage has passed.

To the extent that this factor is important, one is obliged to use pilot-centered handling qualities features. The use of engineer-centered features can require the sophistication of parameter identification, perhaps an undesirable and unnecessary complication.

Also, as discussed earlier, if testing requires task execution (as opposed to simple open-loop inputs) then there must be well defined task performance standards.

B. Roll Control Power Criteria

Roll control power criteria were developed by relating vehicle response rationally to the amplitude of the task flown. This puts the burden of handling qualities specifications on the persons concerned with setting mission requirements.

A variety of control power criteria forms presently appear in the literature. These include time-to-bank, bank angle per unit time, and recently (as a result of this study) maximum roll rate capability. One common difficulty found in many of these forms is that control power, per se, may not be isolated. Rather, a parameter such as time-to-bank really involves short-term response aspects as well as control power.

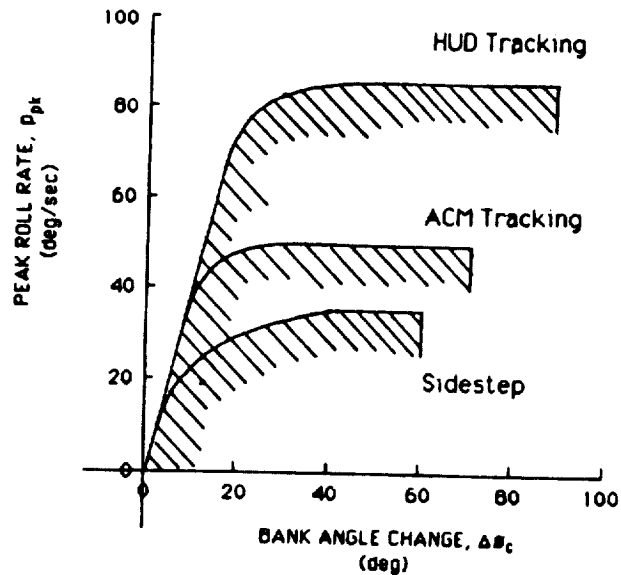
Reference 3 describes in specific terms how time-to-bank requirements can involve both control power and short-term response. In particular, the maximum roll rate attainable is directly reflected in a time-to-bank criterion if short-term response is quick. However, time-to-bank is less of a control power metric and more of a short-term response metric if short-term response is somewhat sluggish. For this reason it may be preferable to rely on a purer control power metric such as maximum roll rate rather than time-to-bank. (This matter will be explored further under the heading of short-term-response criteria.)

Peak roll rate capability was identified as a primary roll control power feature on the basis of examining how tasks and maneuvers were performed by several pilots operating vehicles with various dynamic properties. As shown in Figure 31, a kind of catalog of roll-rate-required can be constructed on a task-by-task basis.

Figure 32 shows how pilot ratings can be normalized on the basis of control-power-available relative to control-power-required for several kinds of tasks or maneuvers. Thus criteria can be set by direct flight measurement of the maneuvering demands. This of course requires that the research flight vehicle be fairly non-limiting, at least in terms of maneuver amplitude performance.

In addition to being a reasonably direct analog to maneuver amplitude, one should note that peak roll rate is a feature directly observable by the pilot. It is therefore both "pilot-centered" and "engineer-centered" as well as being an attribute which is easily expressed in approximate-factor terms.

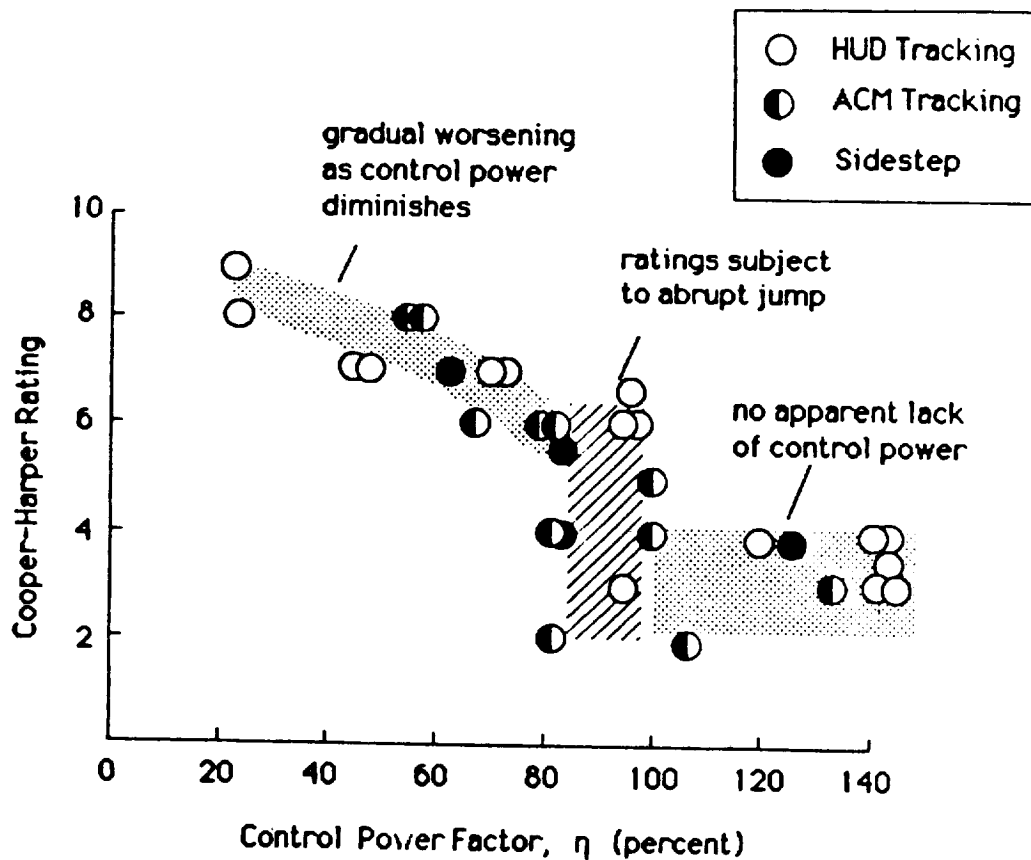
Examples of
Task Demands



Task	Aggressiveness (natural frequency)	Settling (damping ratio)	Amplitude	
			(max roll rate) p_{max}	(max bank change) $\Delta\theta_{c max}$
HUD Tracking	4.0 rad/sec	0.5	85 deg/sec	90 deg
ACM Tracking	2.5	0.5	40-50	110
ACM Free engagement	-	-	40	70
Sidestep	4.5	0.5	35	60
Jinking Maneuver	4.5	0.4	40	50
Slalom	2.0	0.6	30	50
Visual turn	1.5	0.45	40	40
IFR turn	-	-	10	25

Aggressiveness and settling identified for attitude changes $< 10^\circ$.

Figure 31. Catalog of Task Performance Relating to Control Power.



$$\eta \triangleq \frac{p_{\max_{veh}}}{p_{\max_{man}} - 15^\circ/\text{sec}}$$

$p_{\max_{veh}}$ = Maximum Vehicle Roll Rate Capability, degs/sec

$p_{\max_{man}}$ = Maximum Roll Rate Demand for Maneuver, degs/sec

Figure 32. Pilot Opinion Data Plotted Versus Control Power Factor.

Since direct use of the control power factor relationship shown in Figure 32 would produce unnecessarily low control power requirements for very mild maneuvers, it is recommended that a more conservative interpretation be made. Namely, control power should be set as a simple proportion to the observed maneuver roll rate based on the largest maneuver observed, i. e., the HUD tracking task. Thus using the results of this task which has a maximum peak roll rate of 90 deg/sec, the Level 1 control power factor would be 83% and Level 2, 67%.

C. Short-Term Response

Selection of criteria for this feature is difficult. There are many parameters now in use. As with control power, some are direct indications of short-term response while others involve both control power and control sensitivity.

1. Time-to-Bank Criteria

Figure 33 illustrates how peak roll rate can vary with short-term response (roll time constant in this case) for various roll control power metrics in current use. This implies that time-to-bank or bank-angle-per-unit-time can permit a wide range in roll rate capability. For example, a 1 sec time-to-30 deg (t_{30}) involves a 1/3 larger peak roll rate for a 2 rad/sec response than for a quicker 4 rad/sec one. This is actually in fair agreement with the results presented earlier in Figure 21 for Level 1 operation. However this is contrary to the Level 2 results which show that rather low peak roll rates are needed as the response becomes very slow.

Unfortunately there is still a need for better determination of the forms of short-term response and control-power criteria as they covary. There is a danger of being unintentionally arbitrary in choosing handling parameters such as time-to-bank. Further, the results presented earlier show that there is substantial variation with the type of task and how it is performed.

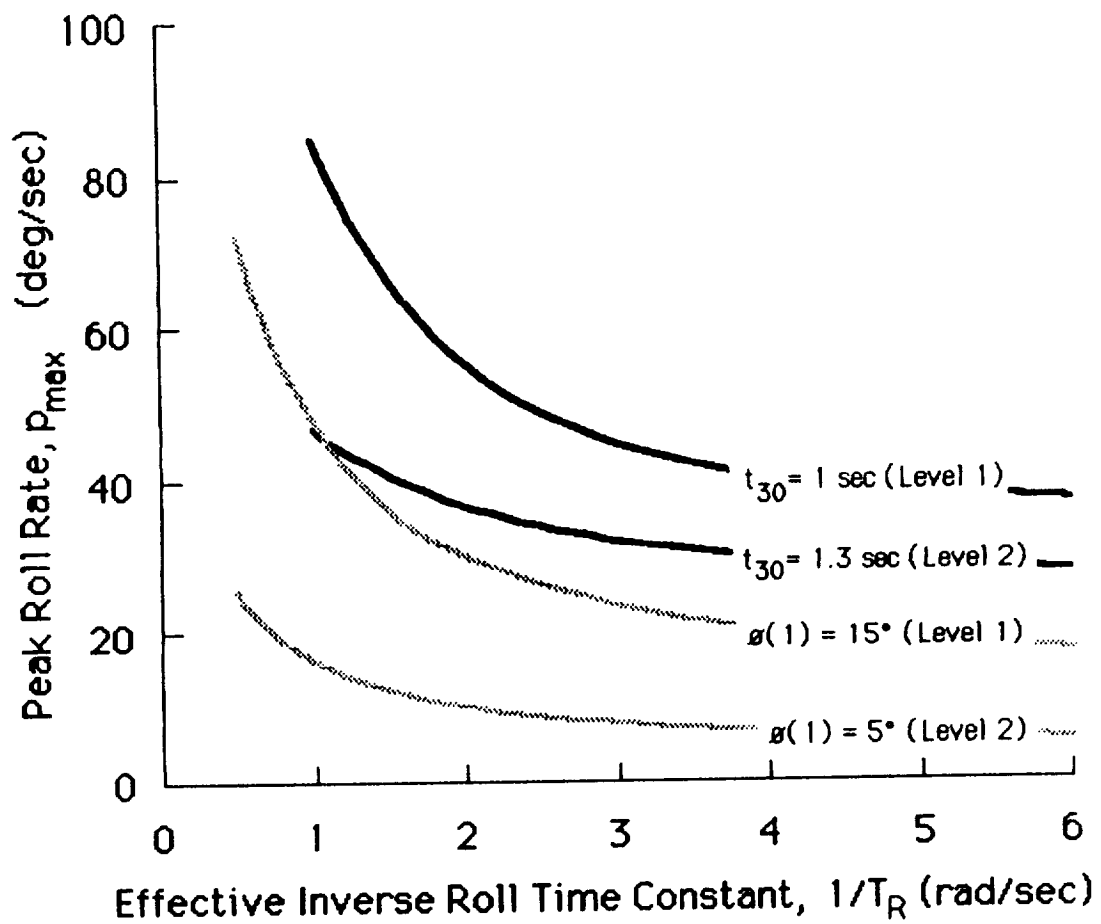


Figure 33. Peak Roll Rate as a Function of Roll Damping and Various HQ Metrics.

2. Bandwidth Criteria

There is also a need to assess properly the basic effects of "bandwidth," response type, and delay. This is complex because all three dimensions are present in the short-term response and can have subtle, task-dependent interactions. The existing body of short-term response handling data is unfortunately not sufficiently precise or consistent to unravel the sometimes subtle distinctions.

Bandwidth at 45 deg phase margin is a metric presently in wide use for defining short-term response. In this study flapping stiffness and roll damping were converted freely to bandwidth. Also various response types were each converted to bandwidth terms. However there is some evidence that such manipulations need to be made with caution as seen in the ACM short-term response data from Figure 28. Note that three response-type cases each had the same bandwidth yet produced radically varying ratings as a function of the range-to-target task parameter.

3. Pilot-Centered Qualities

Another complication is confusion of handling qualities metrics in the qualitative assessment of "quickness." It was observed repeatedly that even experienced evaluation pilots could not distinguish control sensitivity from short-term response and, in fact, spoke only in terms of response quickness. This is a prime example of how "pilot-centered" terms differ from "engineer-centered" ones. This issue is central to improving and refining handling qualities criteria.

4. Delay Properties

The effects of delay may not be treated correctly at present. Some investigations have concluded that there are delay thresholds of some 100 to 140 msec below which there is not significant pilot rating degradation.

The delay data obtained here indicate that even 100 msec of delay can degrade from a Cooper-Harper 2 to 6 if the task is evaluated under critical conditions. One can see from the general rating degradation trends in the critical region that the effect of delays less than 100 msec are likely fairly linear for the data point cited above.

5. Time- and Space-Loading

The most significant contribution to short-term response criteria by this study is identifying the task- or mission-performance dependencies. This was done for both the lateral sidestep and ACM tracking tasks.

Figure 34 shows how the effective bandwidth for a natural helicopter response must vary in order to perform a sidestep or lateral unmask/remask at varying rates. This is compared to the presently proposed MIL-H-8501 bandwidth requirements of Reference 2 (which guarantee a 9.5 sec task duration).

A companion criteria plot for the ACM tracking task is shown in Figure 35. The proposed 2 rad/sec bandwidth would permit a Level 1 mean range to target of 600 ft while increasing bandwidths could permit moving in up to 200 ft closer.

The basic issue raised by the above is whether handling criteria need to be associated with basic mission performance requirements such as the time required to perform a given mission segment. Heretofore this has been avoided.

In the case of the lateral unmask/remask there is a fundamental question of survivability in being able to transit an exposed area one or two seconds faster than other criteria may permit. That time could be crucial to avoiding a threat radar to lock on to its target.

Likewise, for the ACM tracking task, the bandwidth can be associated with how close one can track a target hence how effective the probability of kill. Again this is a mission performance issue dictated by a handling qualities parameter. Similar inferences can be drawn for varying response types.

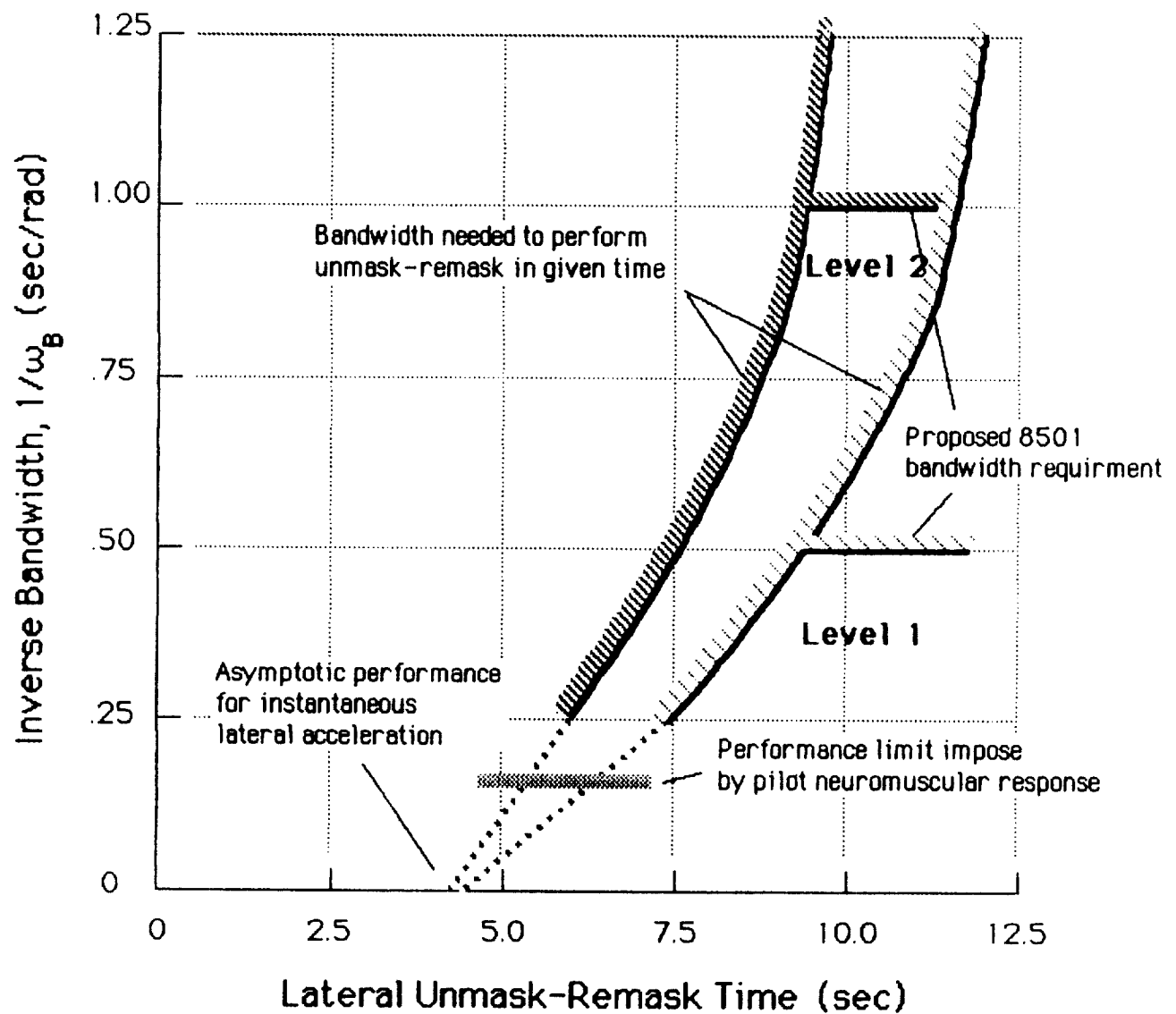


Figure 34. Handling Qualities Levels as a Function of Bandwidth for the Lateral Unmask/Remask Maneuver.

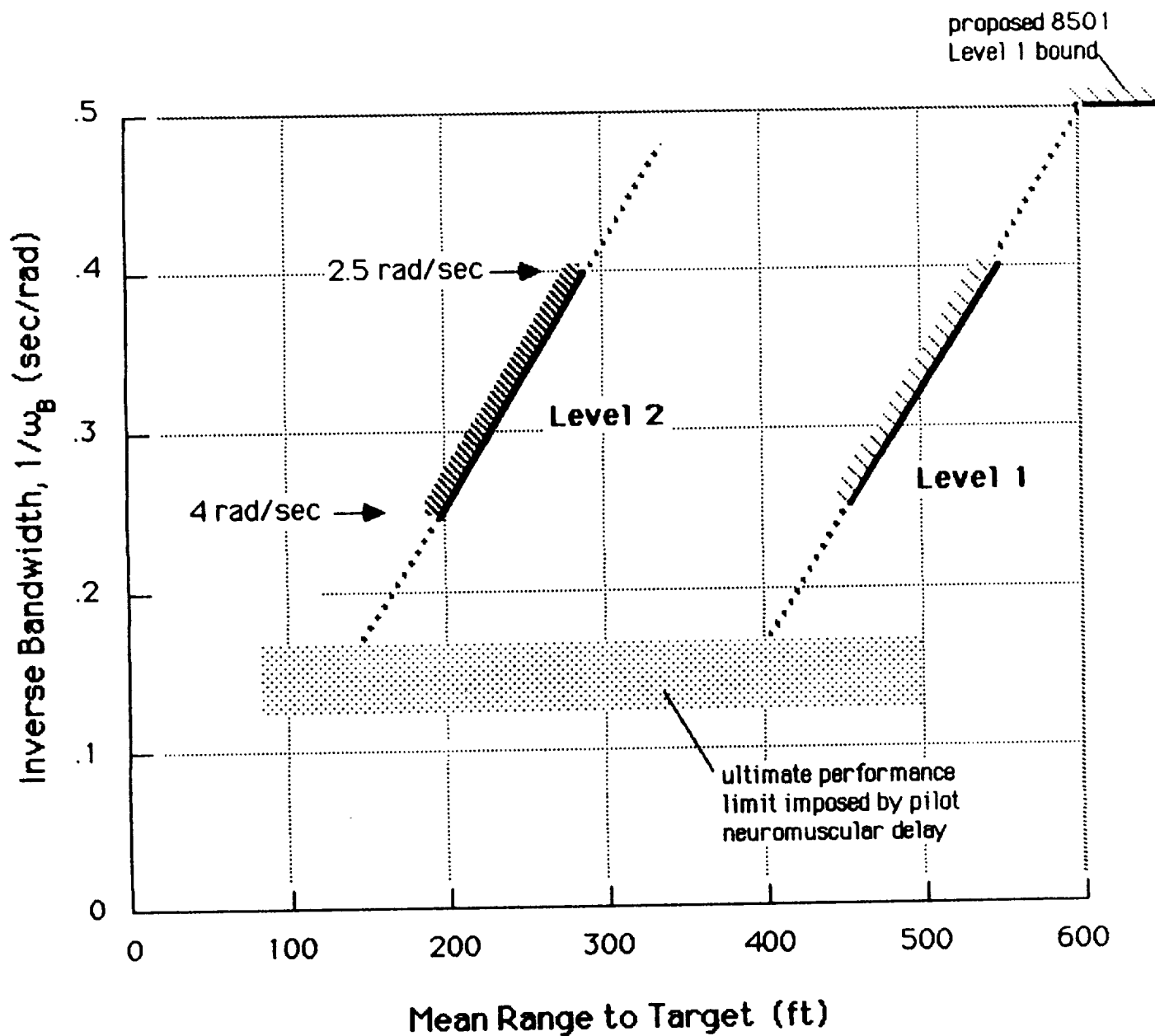


Figure 35. Handling Qualities Levels as a Function of Bandwidth for the ACM Tracking Task.

D. Control Sensitivity

Control sensitivity was not a primary objective of this study, however simulator experiments yielded some results concerning criteria that are worth reporting.

It was observed that optimal control sensitivity appeared to follow roll rate per unit control deflection or force amplitude at a given operating frequency. This is compatible with the idea that the maximum roll rate used for a given maneuver tends toward a consistent value among both different pilots and configurations.

In general, a value of 15 deg/sec/in at 2 rad/sec provided a near-optimum control sensitivity in the roll axis. This is compatible with the MIL-H-8501A static control sensitivity upper bound when roll damping is fairly high.

The above simulator results should be reevaluated in flight, however, since pilots in simulators tend to prefer slightly higher sensitivities than in flight.

There is also a need to recognize confusion among the properties of control sensitivity, control power, and short-term response. Pilots do not seem to distinguish these very well, but tend to lump all as "quickness." This is not considered a particular fault or shortcoming of pilots because their primary job is to fly not self-analyze. But this should be recognized by the engineer, especially where comments are being interpreted for the purpose of diagnosing cause and effect.

Another factor is the distinction between control force and deflection. There are strong, differing opinions on the relative importance of each. Unfortunately the supporting evidence for either side is not clear. The predominance of force or deflection as a metric probably varies depending upon task, axis of control, aircraft type, and pilot background or preference. For example, many helicopter pilots should be less attuned to force since most older designs are typically flown without a force feel system operating.

E. Augmented Control Response Type

Thorough treatment of handling qualities criteria for highly augmented control response types has not been made either in this study or others. It is a complex issue because:

- (i) response features can vary widely in terms of degrees of freedom,
- (ii) task applications can have individual needs,
- (iii) pilot background and training is important, and

(iv) manipulator characteristics have great influence.

Nevertheless some lessons were learned here which should be used in shaping future research.

1. Computational Effects

Simulator results, especially those obtained during the first phase, were seriously affected by computational effects. High-gain feedback loops were not possible to solve because the simulator computer cycle time was too slow. In addition, the effective throughput delay in the visual output precluded tight manual control. Any attempt to base criteria on such results would reflect only the limitations of the simulation system rather than basic flight characteristics.

2. Manipulators

Some highly-augmented response types also involve augmented artificial feel and manipulator systems. These were found to be especially difficult to understand and manage on the simulator and, more important, could have a profound effect on whether a given task could be performed.

Following the second phase simulation period wherein the lateral sidestep data were obtained, a brief third simulation was set up to repeat several points. The only element which could not be precisely reproduced during this last session was the manipulator. Rather than using the earlier conventional center stick controller a sidestick controller was used. This single component prevented the pilot from even successfully performing the sidestep maneuver much less examining degraded configurations.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. Handling Qualities Criteria

1. General

Criteria must be treated conditionally according to task, at least, and according to pilot and environment if possible. Control power criteria will generally depend upon "task-amplitude" and short-term response criteria upon "task-duration" and "aggressiveness."

The application of criteria proposed from prior research should be made with careful consideration of the tasks involved in development of those criteria.

2. Control Power

Roll control power criteria found useful for the designer are based on uninhibited performance of respective maneuvers. These can be determined during actual flight demonstrations and possibly extrapolated from simulation.

For a given maneuver, roll rate limiting is a phenomenon exhibited in both flight and simulation. For increasingly large bank angle changes the proportion of peak roll rate tapers off. This is equivalent to maneuver aggressiveness decreasing as maneuver amplitude increases.

The maximum level of control power used was observed during the single-axis HUD tracking task. The maximum peak roll rate for this task was approximately 90 deg/sec.

Vehicle control power requirements can be rationally based on the task amplitude demands because of the simple cause and effect relationship.

The required maximum roll rate capability to ensure Level 1 operation should be 83% of the maximum observed roll rate for a given maneuver and, for Level 2, 67%.

3. Short-Term Response

Short-term roll response criteria need to be effectively separated from roll control power criteria, thus the use of conventional bank angle per unit time or time to a given bank angle is undesirable.

A number of short-term response parameters can possibly be used interchangeably, including roll time constant, bandwidth, and effective flapping stiffness. This is true because there is a fairly unique mapping among them all.

Short-term response requirements are highly conditional on the specific time loading, task duration, or task aggressiveness.

Effective flight control system delay is a powerful ingredient in short-term response and plays a large role in determining outer-loop task performance potential.

At the same time, transport delay in flight controls is insidious in that the effect may not be detected until the pilot is severely challenged to respond quickly or with a high loop gain in the pilot-vehicle system.

Short-term response is a factor in performance of the air combat tracking task in terms of how close a range the attacker can maintain with respect to the target aircraft. Specific features having an effect were effective bandwidth and flight control system response type. From inference, transport delay would have a similar influence.

Transport delay can be detrimental to task performance, even when delay is present in amounts heretofore believed benign. For a critical combination of vehicle response and task duration, 100 msec was observed to degrade pilot rating from a 2 to a 6.

The use of any short-term response criterion such as "bandwidth," "flapping stiffness," or "rise-time" should be quantified for individual response types since they can affect task performance in the "critical" range.

The presently proposed bandwidth requirements may be unnecessarily restrictive with respect to mission performance as seen in the data obtained for both the lateral unmask/remask and ACM tracking tasks.

B. Research and Experimental Techniques

1. Performance Measurement

Testing procedures are crucial to minimizing scatter in results, especially pilot opinion ratings. Where such procedures tend to ensure consistency in all aspects of task performance then pilot ratings tend to be consistent and repeatable.

Permitting the evaluation pilot to set time-loading aspects of task performance invites unintentional variation in pilot ratings.

The practice of managing task performance standards (considering them as an experimental variable) along with varying vehicle characteristics is crucial to obtaining pilot rating data with minimal scatter.

The use of the timed task duration is one practical technique for monitoring and controlling important aspects of task execution.

Direct measurement of discrete-maneuver features such as peak roll rate and net bank angle change is another practical means for examining task performance directly.

On-line measurements are crucial for conducting efficient experimental programs whether on a simulator or in flight.

2. Ground Simulation

Ground-based simulation appears to have considerable value in establishing criteria and especially criteria structure where there are means of adjusting simulation results with in-flight data.

Simulator results can be affected by a number of factors associated with excessive math model and simulator system complexity. These factors include computational speed, throughput delay, spurious and unintentional math model features, and outright errors in software or math model parameters.

One important role of ground simulation is to explore maximal pilot performance attributes such as was done in the HUD tracking task.

3. Flight Test and In-Flight Simulation

Direct comparison of maneuvers performed in flight and in the simulator is a useful step in assessing simulator effectiveness. However, this must be accomplished through careful measurement of task or maneuver performance features.

Regulated task performance procedures such as the timed task duration should be regularly considered when collecting flight data.

C. Mission/Task Quantification

Steps taken to enhance the quantification of mission and flight task performance can aid in the search for rational handling qualities requirements.

1. Taxonomy

It is possible to quantify task performance features in a manner which is parallel to vehicle response and performance. This provides the basis for task- and mission-dependent handling qualities requirements.

Task time-loading effects are strong factors in establishing handling qualities requirements. Time-loading is closely tied to short-term response qualities which, in turn, are instrumental to quick, precise, and settled execution.

A crucial factor in defining desired and adequate performance is the amount of settling required of the pilot.

Amplitude of task or maneuver is effectively characterized by peak roll rate for rate-response-type systems although there can be a fairly wide range of bank angle commands involved.

For attitude command response type systems the net bank angle change best characterizes amplitude. The reason for this is that roll rate is more strongly determined by the tight control system than by the pilot. Thus peak roll rate is not as meaningful a metric for this kind of system as it is for rate-command or for lightly-augmented helicopters.

2. Connection with Cooper-Harper Scale

The use of the Cooper-Harper rating scale is based on the careful definition of "desired" and "adequate" task performance. These standards need to be set using the list of task performance attributes such as used here in order to assure uniformity among pilots and the comprehension of results by engineers.

A wide range of pilot ratings are possible for any configuration unless task performance standards are carefully defined. Beyond simple precision, maneuver aggressiveness was found to be a particularly crucial feature. This was manifested as task duration for the lateral sidestep and range-to-target in ACM tracking. The insidious aspect of these task features is in the sometimes-subtle and unintentional variation by the pilot.

Use of the Cooper-Harper rating scale requires the evaluation pilot to articulate decision tree choices in addition to considering pilot demands and aircraft characteristics. Strict enforcement of this practice is encouraged in order to promote consistency in ratings and provide detailed information to the engineer.

One crucial factor in setting performance standards for a complex (multiloop) task is the degree of settling and precision for the inner-loop task. In particular one needs to establish a reasonable roll attitude and decay of rate in order to define acceptable completion of a maneuver such as the sidestep. Without this it is possible for the pilot to finish with a large residual roll PIO and yet maintain fairly tight lateral position bounds. This condition would not permit graceful transition to another task segment, however. It should also be noted that setting a settling standard on the inner loop is really equivalent to bounding phase margin for the closed-loop pilot-vehicle system.

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16. Abstract A study of helicopter roll control effectiveness is summarized for the purpose of defining military helicopter handling qualities requirements. The study is based on an analysis of pilot-in-the-loop task performance of several basic maneuvers. This is extended by a series of piloted simulations using the NASA Ames Vertical Motion Simulator and selected flight data. The main results cover roll control power and short-term response characteristics. In general the handling qualities requirements which are recommended are set in conjunction with desired levels of flight task and maneuver response which can be directly observed in actual flight. An important aspect of this, however, is that vehicle handling qualities need to be set with regard to some quantitative aspect of mission performance. Specific examples of how this can be accomplished include a lateral unmask/remask maneuver in the presence of a threat and an air combat tracking maneuver which recognizes the kill probability enhancement connected with decreasing the range to the target. Conclusions and recommendations address not only the handling qualities recommendations, but also the general use of flight simulators and the dependence of mission performance upon handling qualities.					
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